Volume 18 Number 11

BULLETIN
of the
AMERICAN ASSOCIATION OF
PETROLEUM GEOLOGISTS

NOVEMBER, 1934

ZONES IN ALBERTA SHALE ("BENTON" GROUP) IN FOOTHILLS OF SOUTHWESTERN ALBERTA[1]

J. B. WEBB[2] AND LEO GEORGE HERTLEIN[3]
Jellicoe, Ontario, and San Francisco, California

ABSTRACT

The importance of lithologic and fossil zones in the Alberta shale, more commonly known as the "Benton" formation or group, in the foothills of the Rocky Mountains in southwestern Alberta, is indicated. The territory covered extends for 350 miles along the foothills belt. "Alberta shale" is a group term which includes three formations, in ascending order, the Blackstone, Cardium, and Wapiabi. There are many objections to the use of the terms "Benton" or "Colorado," as either formation or group names in Alberta, and such usage should be discarded. Each of the three formations maintains a nearly uniform thickness northwest of Bow River, but toward the southeast the Blackstone and Cardium formations diminish in thickness, and the sandstone members of the Cardium become erratic in their distribution. Each formation is conveniently divided into zones or members, based on distinct lithologic differences, which were extremely useful in mapping and correlation on account of their persistence, for the most part, throughout the region. Fossil zones recognized are named, in ascending order, the Barren zone, the *Inoceramus labiatus* zone, the *Scaphites ventricosus* zone, and the *Baculites ovatus* zone. The Blackstone formation is of Lower Colorado (Turonian) age, the Cardium and the lower part of the Wapiabi are of Upper Colorado (Emscherian or Coniacian) age, and the uppermost part of the Wapiabi is of early Montana (Santonian) age.

INTRODUCTION

The purpose of the writers is to describe the stratigraphy of the Alberta shale, more commonly known as the "Benton" formation or group, which is one of the most widely distributed stratigraphic units occurring in the foothills of southwestern Alberta. The region under

[1] Manuscript prepared, May 23, 1932. Revised manuscript received, September 10, 1934. Published by permission of the Hudson's Bay Oil and Gas Company, Ltd., Calgary, Alberta.

[2] Formerly geologist, Hudson's Bay Oil and Gas Company, Ltd. Present address, Agaura Explorations, Ltd.

[3] Assistant curator of paleontology, California Academy of Sciences, San Francisco. Formerly geologist with Hudson's Bay Oil and Gas Company, Ltd.

discussion is bounded at the south by the Mill Creek area, which is located south of Crowsnest River in Township 5, and extends northward and northwestward for approximately 350 miles to Berland River, in Township 55. The first part of the paper deals with the lithologic characteristics of the formations, emphasizing particularly the zones which were recognized. These zones proved to be extremely useful in detailed mapping of intricate structures and in correlations within the foothills belt. The second part describes the fossil zones and indicates certain correlations which may be made, on the basis of the faunas, with the Cretaceous sections of other well known regions.

In 1927 the senior writer, with Robert McNeely, made a reconnaissance survey of the territory between Bow and Brazeau rivers. During the field season of 1928 the investigation was continued northwestward as far as Berland River, and in 1929, with the assistance of the junior writer, more detailed work was done in some parts of the region covered during the previous two seasons, and investigations were extended southward to the Highwood River area. In 1930 some additional work was accomplished in this southern territory, and in 1931 several sections were measured in the Crowsnest River area, farther south.

ACKNOWLEDGMENTS

The writers wish particularly to thank F. H. McLearn, of the Geological Survey of Canada, Ottawa, and P. S. Warren, of the University of Alberta, Edmonton, for their determinations of the fossils collected in 1927 and 1928, respectively. Thanks are also extended to those colleagues who have materially helped in collecting field data or in preparation of the manuscript. In this connection, the writers are specially indebted to Robert McNeely, Delmer L. Powers, and Jas. K. Millar.

PREVIOUS WORK

Malloch (18)[4] established the succession of the Cretaceous marine group in the central part of the Alberta foothills through his pioneer work of 1908 in the Bighorn coal basin. He named the three divisions comprising this group, in ascending order, the Blackstone shales, the Bighorn formation, and the Wapiabi shales. Malloch concluded that the Blackstone was probably equivalent to the lower part of the Benton as recognized by Cairnes (3) in the southern foothills, also that fossils which he collected from the middle part of the Wapiabi indicated uppermost Colorado age for this horizon, indeed very near Montana age.

[4] Numbers in parentheses indicate references at end of article.

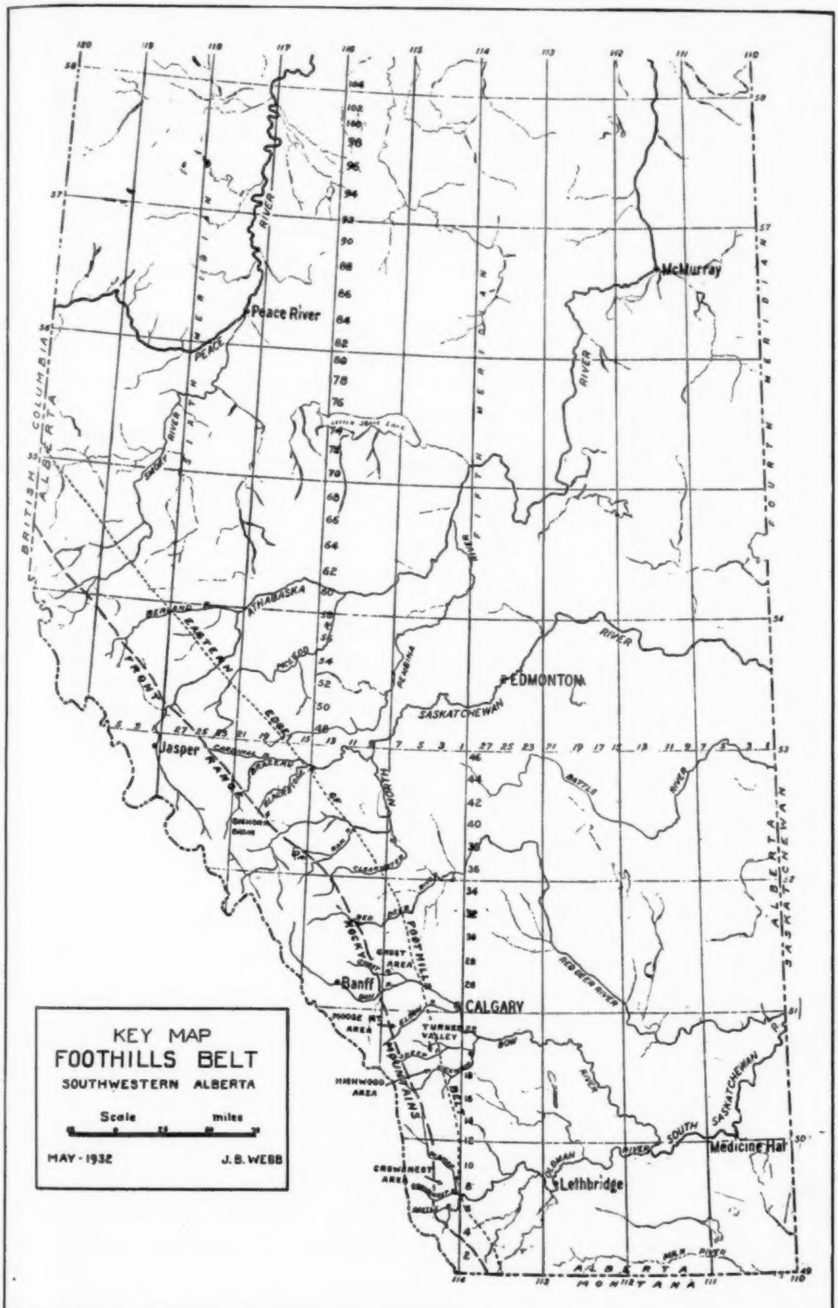


Fig. 1.—Key map of Foothills belt, southwestern Alberta.

The contributions to knowledge of the areas east, northeast, and north of the Bighorn basin through the work of Allen (1, 2), Rutherford (24), MacKay (15, 16), and Warren (32, 33) have extended the use of Malloch's nomenclature. MacVicar (17), in his investigations of that portion of this region which lies north of Athabaska River, assigned the names "Berland River shales" and "Upper sandstones and shales" to strata which are undoubtedly the Blackstone, Bighorn, and Wapiabi formations.

Farther south, in the Bow River area, Rutherford (26) established the divisions known as Lower Benton formation, Cardium formation, and Upper Benton formation, and suggested their correlation with the Blackstone, Bighorn, and Wapiabi formations, respectively. The complete equivalence of the formations was confirmed by the senior writer and McNeely during the field work of 1927.

The investigations by Slipper (29) in the Sheep River area and the surveys by Hume (11, 12, 13) between Highwood River and Jumpingpound Creek are well known. Farther south, Stewart's work (31) has contributed to the general knowledge of the foothills formations. The classification of the Colorado and Montana faunas by McLearn (20), for the Blairmore region, was an important step forward in the study of the formations.

The misuse of the term "Benton" in Alberta foothills nomenclature was indicated by Hume (11), who, more recently, proposed the names Upper and Lower Alberta shale (13) to replace the commonly accepted terms Upper and Lower Benton. In the opinion of the writers, Alberta shale, as a group name to replace "Benton" or "Colorado" as these have been applied in the past in foothills areas, is a valuable addition to the nomenclature. However, the locality names given to the three formations by Malloch might readily be extended to cover the region south of the Bighorn basin. On the basis of priority alone, the names Lower Benton and Upper Benton will be replaced by the more suitable and suggestive Blackstone and Wapiabi, respectively.

In his choice of a name for the middle formation of the group, Malloch was ill-advised in using the term Bighorn, since it had been applied previously to one of the Paleozoic formations of Wyoming (5). Therefore it is proposed that the name used in the Bow River area, that is, Cardium formation, be extended northward in its application, replacing Bighorn in the nomenclature of the group. The original use of the former term by Hector in 1858 (7) was much more inclusive stratigraphically, but Cairnes (3) restricted the name to the sandstone beds and the intervening shales, and described a general-

ized section as observed in the vicinity of Old Bow fort on Bow River. Cairnes referred to these beds as the "Cardium sandstones"; Rutherford (26) later described the same strata in this area as the Cardium formation.

During the summer of 1928, Evans (6) measured numerous sections of the Blackstone, Cardium, and Wapiabi formations in the foothills region between Bow and North Saskatchewan rivers.

BLACKSTONE FORMATION

GENERAL STATEMENT

The Blackstone formation comprises a series of dark gray-to-black marine shales, generally well bedded and of fairly fine texture, which conformably overlies the Blairmore formation and, at the top, is gradational into the basal sandstone member of the Cardium formation.

In the northern areas, the formation underlying the Blackstone shale has been variously termed Dakota or Kootenay. The uppermost member has been given locality names such as Mountain Park formation (Mackay, 15, 16), McLeod member (Rutherford, 25), and Sunset sandstone (MacVicar, 17). The results of field work between Bow and North Saskatchewan rivers yield correlations which indicate that all of these formations are wholly or partially equivalent to the Blairmore.

In the territory south of Oldman River, in the inner foothills, the Blackstone (so-called Colorado) overlies the Crowsnest Volcanics, a formation which is generally believed to be interposed between the so-called Colorado and the Blairmore. Studies conducted by the senior writer strongly suggest that the Crowsnest Volcanics is simply an areally developed facies of the upper part of the Blairmore formation. In the eastern part of the foothills in this region, the intercalations of volcanic tuff are absent, and the upper Blairmore strata are of normal aspect.

The Blackstone formation is approximately 900 feet thick on Ghost River. Farther north very few satisfactory, complete measurements were obtained, but the thickness is not believed to exceed 1,000 feet in this part of the region. General thinning takes place southward from Ghost River, and the formation is only 450 feet thick in the Crowsnest area.

The contact between the marine Blackstone shales and the underlying typically fresh-water deposits of the Blairmore formation is abrupt, without any indication of an intervening period of transition between a totally continental and a wholly marine environment.

The invasion by the Lower Colorado sea was evidently a steady, transgressive movement and possibly took place at a relatively rapid rate. Wherever observed, the contact between the marine and fresh-water strata appears quite conformable, but it is realized that the relationship may be disconformable.

In that part of the region between Pincher Creek and Ghost River the "grit bed" is generally present at, or just above, the base of the Blackstone shales. This distinctive sandstone may consist of a few very thin bands or a solid bed up to 15 feet thick. The grains consist chiefly of cherty material and are angular or grit-like, and in places coarse enough to be conglomeratic. Fish scales and bones occur plentifully in the grit bed at some localities. Hume (13) used the grit zone as marking the contact between the Blairmore and the Lower Alberta shale (Blackstone).

At the top, the Blackstone shales are conformably overlain by the sandstones and shales of the Cardium formation. The change from the sandy shale, with brown-weathering iron-stone concretions, of the uppermost Blackstone to the basal sandstone member of the Cardium formation is generally gradational. The contact between the two formations is therefore arbitrarily drawn at the base of the lowest sandstone band in this transition zone.

The noteworthy features of the Blackstone formation are the uniformity and continuity of the lithologic and faunal zones within the formation throughout this portion of the foothills belt. However, in the Berland River district a generally sandier composition marks the inception of a northward change in the sediments deposited in the Blackstone sea.

LITHOLOGIC ZONES

The Blackstone formation is readily divisible into several broad lithologic zones which are summarily described in Table I. The entire formation is present and almost completely exposed on Ghost River in Sec. 33, T. 26 N., R. 7 W., 5 M. There is believed to be about 200 feet of repetition in this section due to thrust faulting. Table I gives the stratigraphic thicknesses of the zones with repetitions eliminated.

These zones are persistent, mappable units throughout the region, except at the extreme north end of the territory where the middle and upper parts of the Blackstone contain more sandstone intercalations than are found farther south. Some of these beds may be confused in mapping with very similar shales occurring in the higher Wapiabi formation. The Transition zone sediments, like certain parts of the Wapiabi, are characterised by the presence of numerous brown-weath-

TABLE I

LITHOLOGIC ZONES, BLACKSTONE FORMATION

Thickness (Feet)		*Description*
		Overlying beds—basal sandstones of Cardium formation
100	Transition zone	Sandy, dark gray shale with small, brown-weathering ironstone concretions along bedding planes; a few thin, very fine-grained, hard sandstone ribbons. Rare *Inoceramus* cf. *corpulentus*. This is only part of Blackstone that contains numerous rusty brown-weathering concretions. It forms a Transition zone between underlying shales and overlying Cardium sandstone
150	Rusty Shale zone	Fine-grained, sandy, dark gray-to-black shales, weathering to slightly rusty tinge contain few concretions which weather yellow-brown, lenticular, and up to 3 feet in diameter. Thin bentonite seams. Fossils absent. Termed "Rusty Shale" zone in contrast to underlying zone, the shales of which do not weather rusty
300	*Inoceramus labiatus* zone	Finely bedded, black clay shales with very thin, fine-grained, gray sandstone laminae. Upper part holds a few lens-shaped, gray, calcareous concretions. In middle, discontinuous bands up to 2 feet thick of hard, fine-grained calcareous sandstone or argillaceous limestone. These beds gray-to-black on fresh surface but weather dirty yellow. Basal portion, fine, fissile, black clay-shale with a few gray calcareous concretions. Bed of bentonite and volcanic ash up to 2 feet thick marks base of zone at some localities. *I. labiatus* Schlotheim is common and *Prionotropis* sp. occurs. "*Inoceramus labiatus*" zone of Warren and Rutherford (25) in somewhat restricted sense
350	Barren zone	Sandy, rusty-weathering shale with thin, hard, sandstone ribbons and a few thin, concretionary, calcareous bands, or, at some localities, large masses. Platy-to-massive sandstone bed up to 4 feet thick occurs about 100 feet above base. Fish scales generally abundant in sandstone. At base, 2 feet of coarse conglomeratic sandstone ("grit bed"), present. *I.* cf. *corpulentus* and *Acanthoceras albertense* Warren very rare. Interval was well-named "*Barren*" zone by Warren and Rutherford
Total 900		Underlying beds—sandstones and shales, light gray and green, Blairmore formation

ering ironstone concretions; it is therefore necessary to establish the stratigraphic relations, such as the position with respect to the Cardium formation, when classifying these shales. The Rusty Shale zone is distinctive of the upper part of the Blackstone. The finely interbedded shales and sandstones of the *Inoceramus labiatus* zone give the middle part of the formation a platy appearance on outcrops similar to the middle beds of the Wapiabi. There are thick layers of fissile, black clay-shale in this zone of the Blackstone, however, which are unlike any part of the higher formation. The fossils are generally numerous in these fine shales, and *I. labiatus* or the small *Prionotropis* sp. are indices of this horizon. The sediments of the Barren zone are not readily mistaken for any of the higher shales.

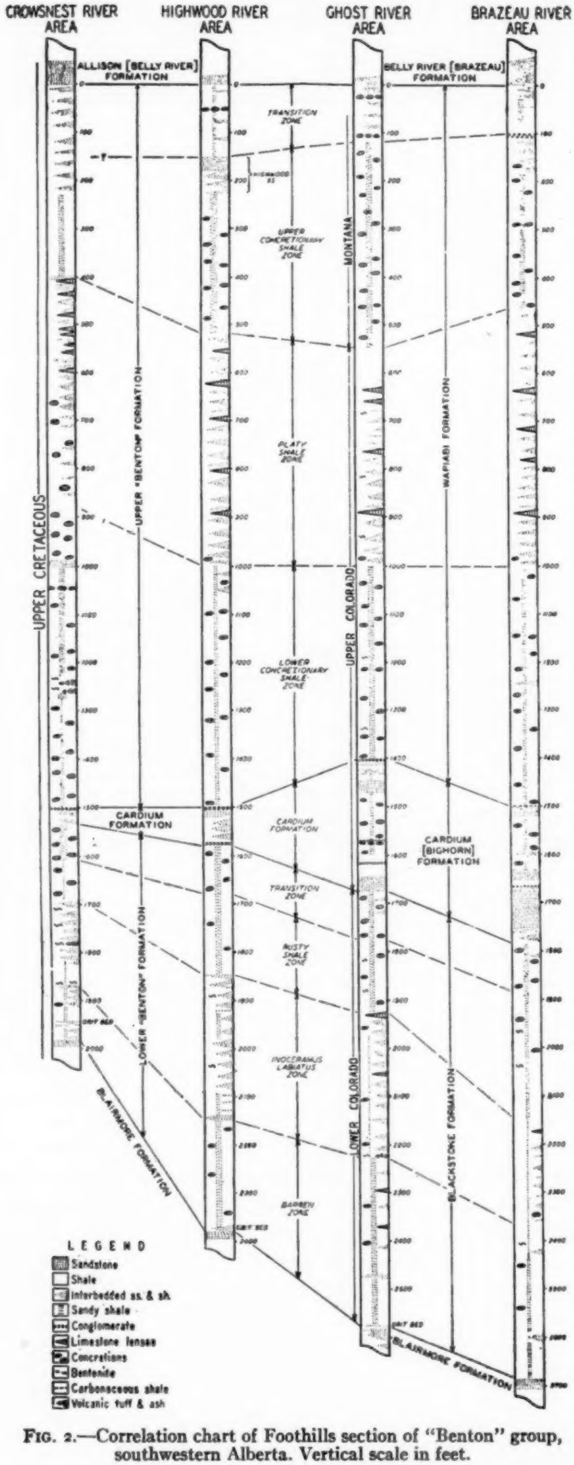


Fig. 2.—Correlation chart of Foothills section of "Benton" group, southwestern Alberta. Vertical scale in feet.

In working out the details of structure in the foothills, where compressive forces have caused overturning and extreme repetition of strata by thrust faulting, the broad zones outlined have proved very useful. Locally, these zones may be subdivided into smaller units for detailed mapping.

It is interesting to note that, at the south end of the region, where the Blackstone is only 450 feet thick, all of the zones observed farther north are present, though proportionately thinner. As most of the zones are gradational into each other, the selection of zonal contacts is quite arbitrary, hence considerable variation in the thicknesses is observed. A real thickening of the Rusty Shale zone is apparent in

FIG. 3.—Looking east at east-dipping Cardium formation and uppermost beds of Blackstone formation on Cardinal River, in Sec. 10, T. 45 N., R. 19 W., 5 M. Prominent sandstone bands are in Lower member of Cardium. Transition from Blackstone to Cardium well illustrated. In right background may be seen thin sandstone bands in Upper member of Cardium. Photo by Delmer L. Powers.

the Brazeau River area, where this interval measures 260 feet. The entire Blackstone formation is probably thus thickened in the northern part of the region.

CARDIUM FORMATION

From Bow River northwestward through the central part of the foothills belt for 250 miles or more, the Cardium formation consists of a well defined series of hard sandstone bands and sandy shales, chiefly marine in origin, which conformably overlies the Blackstone and, in turn, is conformably overlain by the Wapiabi formation. On Ghost River and northwest the thickness does not vary much from 275 feet; eastward thinning is evident. On Bow River the formation

is less than 200 feet thick and farther southeast the sandstone beds become erratic in distribution, thus rendering difficult the definition of the limits of the Cardium. In the Crowsnest River area, a single bed of sandstone, with a maximum thickness of 33 feet, represents the Cardium formation; at one locality this thin band is entirely lacking.

The section described below was obtained by correlating and combining several incomplete measurements of the formation made near the Eau Claire trail-crossing on Ghost River in Secs. 32 and 33, T. 26, R. 7 W., 5 M. The Cardium is here readily divisible into three distinct members: an upper sandstone 70 feet thick, a middle shaly member 174 feet thick, and a lower sandstone 31 feet in thickness. A detailed description is given in Table II.

TABLE II

CARDIUM FORMATION

Upper member	*Thickness of Beds in Feet*
Sandstone, massive, fine-grained, hard, light gray, weathers buff or rusty. From 1 inch to 10 feet of conglomerate generally occurs at top of this bed, small pebbles of black, gray, and green chert in siliceous matrix, nodular brown ironstone at top	13
Shale, dark gray, sandy, with hard, gray sandstone bands	8
Sandstone, massive-to-platy, hard, fine-grained, gray-to-buff on weathered surfaces. *Cardium pauperculum* occurs	8
Shale, sandy, dark gray, with a few sandstone bands	18
Sandstone, massive, hard, fine-grained, gray-to-buff on fresh surface, partly rusty on weathering. Ripple marks and worm trails common. Soft shale partings	23
Middle member	
Shale, sandy, dark gray, numerous brown-weathering ironstone concretions and nodular bands along bedding planes, these most common in upper part	100
Conglomerate, sandstone, and ironstone, in descending order, making hard bands, weathering rusty. Pebbles small (0.25–0.5 inch diameter) of vari-colored chert	2.5
Shale, sandy, dark gray, harder in upper part. A few brown-weathering iron-stone concretions	27
Shale, less sandy, fairly soft, lacking concretions	15
Conglomerate, thin lenticular bands with small, vari-colored chert pebbles, shale partings and brown-weathering ironstone lenses in basal part	2.5
Shale, sandy, dark gray, with hard sandstone ribbons up to 3 inches thick, and a few thin lenses of ironstone	27
Lower member	
Sandstone, thinly bedded, gray-to-buff, shale partings	4
Sandstone, massive, fine-grained, light gray-to-buff, but weathers rusty in places. Partly cross-bedded	15
Sandstone and shale interbedded, hard and soft bands	10
Sandstone, hard, fine-grained, massive, ripple-marked at top	2
Total thickness of Cardium formation	275

This tripartite division of the Cardium formation is applicable in the central foothills far northwest of Ghost River. The thicknesses

of the members are variable. In the Ram River area and northwestward at least as far as McLeod River, the Lower member is 75–100 feet thick and consists largely of hard sandstone, whereas the Upper member is only 25–35 feet thick and contains much shale. The total thickness of the formation is generally 275–300 feet. In this part of

FIG. 4.—Ripple marks in hard, fine-grained, quartzose sandstone of Cardium formation, Blackstone River, T. 42 N., R. 17 W., 5 M. Photo by Robert McNeely.

the region, a hard, poorly sorted, greenish gray-weathering sandstone bed, between 10 and 20 feet thick, makes a persistent band in the lower part of the Middle member.

In the Ghost and Bow River territory, also farther south, chert pebble conglomerate bands occur commonly in the Cardium. At some localities lenses up to 15 feet thick are found at the top of the formation and thin beds are present in the lower part. Hume (13) discusses the Cardium sandstone and conglomerate bands of Turner

Valley and adjacent areas, and suggests that individual bands do not everywhere hold the same stratigraphic position. To the senior writer, this condition seemed particularly evident in the vicinity of Bragg Creek on Elbow River, where one prominent band of sandstone and conglomerate occupies a position equivalent to that of the Lower member on Ghost River, and a thin, lenticular bed of sandstone and conglomerate lies 220–300 feet higher in the section. This upper band is, without doubt, discontinuous and therefore a poor horizon marker.

On Ghost River the east-west changes in the lithologic character of the Cardium formation may be observed. Outcrops in Sec. 4, T. 27 N., R. 6 W., 5 M., about 5 miles east of the section previously described show that the sandstones of the Lower member have been largely replaced by shale containing merely a few thin, hard sandstone stringers. It is interesting to note, as previously mentioned, that southward, on Elbow River, the most prominent band seems to be correlative with the Lower member of the Ghost River area, whereas the Upper member has slight representation. In the eastern part of the Highwood River area the Cardium consists of interbedded hard sandstone and conglomerate and shale beds; the total thickness does not exceed 75 feet and is usually much less. Judged by their relationship to the underlying Blackstone shale, these beds, also the hard sandstones of the Cardium cropping out in Turner Valley, are equivalent to the Lower member of the Ghost River area. In Turner Valley, a pebble band 140 feet above the prominent sandstone may represent the Upper member. The sporadic distribution, and final disappearance farther south, of this pebble band, renders difficult the delineation of the upper limit of the Cardium formation along the east side of the foothills belt south of Turner Valley. In the territory on the west, however, Hume reports (13) three distinct bands in places, occurring through an interval of 340 feet; the middle band is thickest and most persistent. Farther south, in the Crowsnest River Valley east of Coleman, the Cardium formation is represented by 33 feet of interbedded hard sandstones and sandy shales, with a 2-inch layer of chert-pebble conglomerate at the top. South of Crowsnest River the Cardium is generally 10–15 feet thick, but at one locality on Castle River this sandstone band is entirely lacking.

The contact between the Cardium and the underlying Blackstone formation is gradational in character, but the contact with the overlying Wapiabi formation, though apparently conformable, is sharply defined. The fine-grained, dark gray shale of the basal Wapiabi directly overlies the top sandstone or conglomerate of the Cardium forma-

tion. A thin band of nodular, brown-weathering ironstone marks the contact in some areas.

It is probable that the sandstone members of the Cardium are the near-shore deposits formed during temporary eastward or southeastward recessions of the Upper Colorado sea. The locally thick

FIG. 5.—Exposure of basal 300 feet of Wapiabi formation, looking south into canyon of South Ram River, Sec. 10, T. 37 N., R. 13 W., 5 M. Strata dip gently west. Falls at bend of river in foreground are due to ledge formed by hard sandstone at top of Cardium formation. Photo by Robert McNeely.

conglomerate beds may be explicable as beach or bar gravels. In the northern part of the region between Blackstone and McLeod rivers, a thin lignitic shale bed occurs just above the Lower member. The carbonaceous material of this layer might have accumulated in a marginal swamp or lagoon. As a whole, however, the Cardium formation represents marine sedimentation.

Cardium pauperculum generally is found in the Upper member in the area between Bow and Red Deer rivers. Farther north a few species of *Inoceramus* are very numerous in the top of the Lower member.

WAPIABI FORMATION

GENERAL STATEMENT

The Wapiabi formation consists of marine shales of varying lithologic character, but all rather sandy and dark gray-to-black in color. The weathered outcrops of certain zones are rusty-to-greenish gray in appearance. Exact measurements of the total thickness are difficult

FIG. 6.—Looking south at west-dipping uppermost Wapiabi and basal Belly River strata, on Blackstone River, in Sec. 28, T. 43 N., R. 16 W., 5 M. Transitional nature of change from marine Wapiabi shales to overlying freshwater Belly River sandstones and shales is apparent. Photo by Prentiss D. Moore.

to obtain, due to the scarcity of complete sections free from minor folding or thrust faulting; these structural complications result in repetitions of strata, which, if not recognized by the observer, give rise to excessively thick formation measurements. In the Ghost River area the correlation of several incomplete sections gave thicknesses varying between 1,400 and 1,500 feet for the Wapiabi formation; the lesser figure is probably closest to the true thickness. Farther northwest, the average thickness is approximately 1,500 feet; southeastward, in the Turner Valley and Highwood River areas, it is between 1,400 and 1,500 feet. In the Crowsnest River area no satisfactory measurement was obtained, though it seemed evident that the thickness does not exceed 1,500 feet.

The abrupt change in lithologic character marking the contact between the Wapiabi and the underlying Cardium formation has already been mentioned. At the top, the Wapiabi shales generally grade into the fresh-water strata of the overlying Belly River formation. The transitional nature of the change is most marked in the Crowsnest River area, whereas in some parts farther northwest a fairly sharp lithologic change defines the formational contact.

The Wapiabi formation also contains well defined lithologic zones which were found to possess remarkable lateral persistence in stratigraphic detail and thickness, though certain areal variations were recognized.

LITHOLOGIC ZONES

The descriptions and thicknesses of the zones recognized in the Wapiabi formation (Table III) are based on various incomplete

TABLE III

LITHOLOGIC ZONES, WAPIABI FORMATION

Thickness (Feet)		*Description*
		Overlying bed—20 feet massive sandstone, light gray-green, in base of Belly River formation
120	Transition zone	Shale, uppermost 40 feet fine, dark gray, with thin, green-gray, fine-grained sandstone ribbons in upper 20 feet. Sandy shale or shaly sandstone band 6 feet thick, with 8-inch yellow-weathering dark gray, hard, concretionary, calcareous band at base, separates upper shale stratum from a lower bed, consisting of 74 feet of fine shale with a few thin sandstone ribbons. About 12 feet above base of this shale a band of yellow-weathering lenticular, dark gray, calcareous concretions up to 1 foot thick occurs. These generally show cone-in-cone structure
430	Upper Concretionary Shale zone	Sandy shale, dark gray, in massive beds approaching sandstone in character with thin zones of more finely bedded shale. Layers and "cannon-ball" concretions of brown-weathering ironstone common. Concretions have septarian structure, showing net-work of calcite veins. *Baculites ovatus* fairly common
450	Platy Shale zone	Thinly bedded shale, fine black clay shale with laminae of gray sandstone 0.5–2 inches thick. Sandstone ribbons contain comminuted carbonaceous material in some places. Hard, fine-grained calcareous, concretionary bands up to 3 feet thick occur throughout zone; they weather dirty yellowish color, but are dark gray on fresh surface, and in some places sandy. A few thin yellow bentonite layers. Brown-weathering ironstone concretions absent. Thin sand laminations give platy character on weathered surfaces. *Ostrea congesta*, *Anomia subquadrata*, *Scaphites*, and *Inoceramus*
400	Lower Concretionary Shale zone	Sandy shales, dark gray, with many small, brown-weathering ironstone concretions present along bedding planes. Certain thin zones without concretions contain fine, hard sandstone ribbons and a few thin, yellow bentonite seams. *Scaphites* and various *Inoceramus*
Total 1,400		Underlying beds—upper sandstone of Cardium formation

measurements obtained at several localities along Ghost River, in Ts. 26 and 27, Rs. 6 and 7 W., 5 M. The section given is of necessity a composite one.

The most important lateral changes in the sediments of the Wapiabi formation occur southward from Ghost River, in the two upper zones. In the Highwood River area a resistant member approximately 50 feet thick, consisting of hard sandstones and sandy shales with ironstone concretions, is present in the uppermost part of the Upper Concretionary Shale zone. This band is known as the Highwood sandstone. The overlying soft shales of the Transition zone are very similar, in general, to the beds of this zone on Ghost River. Hume (13) discusses some variations occurring in the Transition zone in the western foothills on Highwood River, where chiefly fresh-water sediments occupy this interval. Apart from the Highwood sandstone member, the Upper Concretionary Shale zone does not contain as much ironstone in this area, neither is it as sandy and massive as the equivalent beds on Ghost River and farther north.

At the south end of the region in the Crowsnest River area, this upper part of the Wapiabi formation is distinctly different in aspect as compared with the areas on the north. The Transition zone is thicker, measuring 230 feet, and consists of regularly interbedded, hard fine-grained sandstones and dark gray shales. Below these beds is a thickness of 170 feet of very fine-grained, dark gray shale, quite unlike any of the shales of the Upper Concretionary zone of the north. Ironstone concretions or bands seem to be entirely lacking. Underlying these fine shales are the typical thinly interbedded sandstones and shales, with yellow-weathering limestone lenses, of the Platy Shale zone, which resemble in detail the strata of this zone observed throughout the foothills for a distance of 350 miles northwestward. Similarly, the Lower Concretionary Shale zone is typically developed. On Oldman and Castle rivers numerous bentonite seams and associated volcanic ash lenses occur in 50 feet of comparatively soft, sandy shale in the basal part of this zone. A few thin, hard, sandstone bands are present on Oldman River, lying 225 feet above the bentonite and ash horizon. It is possible that these beds are equivalent to the uppermost Cardium sandstone band of the region on the north.

In the Brazeau River area, northwest of Ghost River, the Transition zone is 105 feet thick and consists chiefly of fine-grained dark gray or dark greenish gray shale, with a few yellow-weathering, lenticular, calcareous concretions and numerous thin, greenish gray sandstone bands in the uppermost part. The top of the Upper Concretionary Shale zone is marked by a hard band, one foot thick, con-

sisting of 6 inches of fine conglomerate overlain by an equal thickness of brown-weathering ironstone. Four feet lower in the section another 6-inch conglomerate bed occurs. The strata for 50 feet below this horizon are very sandy, massive shales with a few thin, hard sandstone bands, and ironstone concretions. These resistant beds grade downward into softer shales which contain numerous ironstone concretions. The thickness of the Upper Concretionary Shale zone in this area is approximately 315 feet, which is considerably less than the measurement obtained on Ghost River. It is probable that the apparent northward thinning of this zone is compensated by thickening of the underlying zones, so that the Wapiabi formation as a whole is as thick on Brazeau River as it is on Ghost River—possibly thicker on Brazeau River. North of Brazeau River, in the McLeod River area, a prominent sandstone occurs at the top of the Upper Concretionary zone which is strongly reminiscent of the Highwood sandstone. Such sandstones as these are probably to be explained as local or areal facies of the massive, very sandy shales generally characteristic of the uppermost beds of this zone, and represent conditions of deposition which favored more complete sorting of the sediments being deposited at that time.

The various zones were found very useful in the field in disentangling complicated structures. Some confusion was encountered in determining the position of isolated outcrops of shales bearing brown-weathering ironstone concretions, at certain localities; in such cases the fossil evidence, where available, could be relied on as a sure key to the general horizon represented. *Baculites ovatus* is restricted to the Upper Concretionary zone and the uppermost beds of the Platy Shale zone, whereas *Scaphites ventricosus* is most commonly found in the Lower Concretionary zone, ranging upward through the Platy Shale zone, but, so far, has not been recorded from the Upper Concretionary zone. Some parts of the Platy Shale might be confused with similar beds in the *Inoceramus labiatus* zone of the Blackstone formation, but the fossils are distinctive and, with careful searching, can generally be found in the exposures.

The cycle of marine sedimentation represented by the Wapiabi shales corresponds closely with that of the Blackstone shales. In general, the sediments exhibit the highest degree of sorting in the middle portions of both of these formations. The Wapiabi, however, contains a great number of brown-weathering concretions and thin stringers of ironstone in its upper and lowermost portions; the only part of the Blackstone that is similar in this respect is that concretion-bearing zone immediately below the Cardium formation.

PALEONTOLOGY

GENERAL STATEMENT

The lists of fossils indicate the predominance of the *Pelecypoda* and *Cephalopoda* in number of genera and species. The horizons represented range from Lower Colorado (Lower Turonian) to early Montana (Lower Senonian) age.

The various faunas furnish a good basis for correlation with the Colorado and lower Montana formations in the western interior and Rocky Mountain regions of the United States and also with the standard European section. These faunas would be expected to exist under a marine environment in fairly warm water generally less than 100 fathoms in depth.

FOSSIL ZONES

The conclusions presented herein regarding the faunal zones in the Colorado and lower Montana of the Alberta foothills and their correlations are, except in certain details, in general agreement with the work of Warren and Rutherford (32) and McLearn (20).

The accompanying faunal lists were compiled from the results of collections[5] made by the writers and identified by F. H. McLearn, P. S. Warren, and L. G. Hertlein. The species listed by Warren and Rutherford are also included.

Barren zone.—This unit, which has already been described in this paper as a lithologic zone, was originally named by Warren and Rutherford on account of its general lack of fossils. In the central and northern parts of the region this zone is 350 feet thick but in the southern foothills the thickness is only 110 feet.

The following forms are sporadic in occurrence, except the fish scales, which are generally plentiful in the hard sandy shales or thin sandstones near the base of this zone.

Cephalopoda
  Ammonoidea
    Acanthoceras albertense Warren *Prionotropis* sp.
Pelecypoda
    Inoceramus corpulentus McLearn
Pisces
    Ichthyodectes sp. (scales only)

Inoceramus labiatus zone.—This zone overlies the Barren zone, and was named by Warren and Rutherford (32) due to the widespread and plentiful occurrence of *I. labiatus* at this horizon. McLearn

[5] These collections are deposited at the Geological Survey of Canada, Ottawa; the University of Alberta, Edmonton; and the California Academy of Sciences, San Francisco.

(20) also has described this zone for the Blairmore area. In the north this zone is approximately 300 feet thick, but it is somewhat thinner at the south end of the region. The *Inoceramus labiatus* zone also forms a distinct lithologic unit, as previously described in this paper.

The fossils collected are here listed.

Pelecypoda
Inoceramus labiatus Schlotheim
Ostrea cf. *congesta* Conrad

Pisces
Unidentifiable scales

Ammonoidea
Prionotropis cf. *hyatti* Stanton
Prionotropis woolgari Mantell

Scaphites ventricosus zone.—This broad faunal zone also was recognized by Warren and Rutherford and by McLearn. *S. ventricosus*, or varieties of this species, has been found through a vertical range of 1,100 to 1,200 feet, from beds in the lower part of the Cardium formation up to the top of the Platy Shale zone in the Wapiabi formation.

The list of genera and species recorded from these beds is as follows.

Pelecypoda
Anomia subquadrata Stanton
Cardium pauperculum Meek
Exogyra sp.
Inoceramus cf. *albertensis* McLearn
Inoceramus altus Meek
Inoceramus coulthardi McLearn?
Inoceramus corpulentus McLearn
Inoceramus deformis Meek
Inoceramus exogyroides Meek & Hayden
Inoceramus flaccidus White
Inoceramus fragilus Hall & Meek
Inoceramus pontoni McLearn
Inoceramus selwyni McLearn
Inoceramus umbonatus Meek & Hayden
Inoceramus sp. indet.
Oxytoma nebrascana Evans & Shumard
Pholadomya sp. indet.
Pinna sp. indet.
Pteria cf. *linguiformis* Evans & Shumard

Pisces
Unidentifiable scales

Gastropoda
Anchura sp.
Anisomyon sp.
Turritella? sp.

Cephalopoda

Ammonoidea
Baculites cf. *codyensis* Reeside
Baculites asper Morton
Scaphites ventricosus Meek & Hayden
Scaphites ventricosus var. *depressus* Reeside
Scaphites ventricosus var. *interjectus* Reeside
Scaphites ventricosus var. *stantoni* Reeside
Scaphites vermiformis Meek & Hayden

Baculites ovatus zone.—The *Baculites ovatus* fauna has a vertical range of 500 to 600 feet in the middle and northern parts of the region, occurring in the uppermost beds of the Platy Shale zone and upward through the Upper Concretionary zone into the middle of the Transition zone. *B. ovatus* and most of the associated fauna have not been recorded from the south end of the region, that is, in the Crowsnest area.

The following forms have been recognized.

Pelecypoda

Lingula sp.
Callista? sp.
Cardium pauperculum Meek?
Cymella sp.
Inoceramus lundbreckensis McLearn
Inoceramus sp.
Ostrea congesta Conrad
Ostrea sp.
Oxytoma nebrascana Evans & Shumard
Pteria linguiformis Evans & Shumard
Liopistha montanensis Henderson
Pholadomya papyracea Meek & Hayden
Pholadomya sp.
Pinna sp.
Tancredia americana Meek & Hayden
Tancredia? sp.
Tellina sp.
Tellina? sp.

Cephalopoda

Nautiloidea

Nautilus sp. (resembles *Eutrephoceras alcesense* Reeside)

Ammonoidea

Baculites aquilaensis var. *separatus* Reeside
Baculites ovatus Say
Baculites ovatus var. *haresi* Reeside
Scaphites leei Reeside
Desmoscaphites bassleri Reeside?
Placenticeras sp.

Pisces

Unidentifiable scales

GENERAL DISCUSSION AND CORRELATIONS

COMPARISON WITH PREVIOUSLY ESTABLISHED FOSSIL ZONES

Warren (33) recently described three new ammonites from the basal beds of the Lower Smoky River (Kaskapau) formation of the central Peace River plains area of northern Alberta. The horizon is distinctly below the lower limit of the *Inoceramus labiatus* zone, just above the Dunvegan sandstone. Warren mentions the fact that one of these new species, *Acanthoceras albertense* Warren, also occurs in the basal "Benton" in the foothills far south, on Luscar Creek, where Webb collected one specimen. A similar large, heavily ribbed ammonite was recently found by the senior writer on Castle River, at the south end of the region, where it also occurs in the basal "Benton," that is, the Barren zone of the Blackstone formation. Since it was impossible to bring the specimen in at the time of its discovery, the identification is lacking. However, it would not be surprising to find, with further work, that *A. albertense*, though rather rare in occurrence, characterizes the sparse fauna of the Barren zone.

Warren and Rutherford (32) conclude that *Prionotropis woolgari*, although sparingly present in the Barren zone, marks a distinct horizon above the *Inoceramus labiatus* zone. McLearn (20) also expresses the opinion that *Prionotropis* is characteristic of beds above the *I. labiatus* beds at the south end of the region. Contrary to these ideas, the present writers find that *Prionotropis woolgari*, though rare, occurs only in the fine-grained, fissile shales in which *I. labiatus* generally abounds, and therefore marks neither a higher nor a lower zone than the latter species. At the south end of the territory, the senior writer obtained a few *Prionotropis woolgari* occurring with innu-

merable *I. labiatus* at Mountain Mill on Mill Creek and in the northwest part of T. 6 N., R. 2 W., 5 M., on the north side of Castle River, about ½-mile west of the bridge. Linn Farish[6] concluded, after detailed examination of numerous complete diamond-drill cores of the Lower "Benton" (Blackstone) from holes drilled in the area south of Pinche-

TABLE IV
GENERAL CORRELATION CHART
(J. B. Webb and Leo George Hertlein)

Europe		*Western Alberta*			*Southern Montana*	*Central Plains*			*Colorado-New Mexico*	*Peace River, British Columbia*
SENONIAN	Santonian	ALBERTA SHALE ("BENTON")	Wapiabi	*B. ovatus* Zone	Eagle	MONTANA	Pierre		Mesa Verde	Upper Smoky River
					Telegraph Creek				Mancos	
	Emscherian (Coniacian)			*S. ventricosus* Zone	Niobrara	COLORADO GROUP	Niobrara			
			Cardium							Badheart
TURONIAN	Upper Turonian		Black-stone	*I. labiatus* Zone	Carlile		Carlile	Benton		Lower Smoky River (Kaska-pau)
	Lower Turonian				Frontier		Green-horn			
					Mowry		Gran-eros			
				Barren Zone	Thermop-olis					

[6] Linn M. Farish, geologist, Alberta Gas and Fuel Company, Ltd. Personal communication to senior writer, October, 1930.

Creek, that *Prionotropis woolgari* is plentiful in two very thin layers occurring within the *I. labiatus* zone. It was not found outside the range of *I. labiatus*.

A horizon particularly barren of fossils is the Rusty Shale zone which occupies an interval of 150–260 feet immediately above the *I. labiatus* zone.

Baculites ovatus ranges 200–300 feet lower in the Wapiabi formation according to the present collections, than Warren and Rutherford noted this species.

McLearn (20) obtained a collection of fossils from the *Scaphites ventricosus* zone on Crowsnest River east of Crowsnest Lake. In addition to some of the genera and species already listed in this paper, the following are reported present: *Placenticeras syrtale* (Morton), *Scaphites ventricosus* var. *saxitonianus* McLearn, *Inoceramus undabundus* Meek & Hayden, *Martesia mcevoyi* McLearn, *Pholadomya nitanae* McLearn.

Farther east on Crowsnest River, about 2 miles west of Lundbreck, McLearn collected *Inoceramus lundbreckensis* McLearn and *Baculites* cf. *asper* (Morton). This fauna was regarded as probably post-*S. ventricosus* in age. The containing strata are in the uppermost part of the Platy Shale zone according to the senior author's classification. About 17 miles north, on Oldman River, similar beds of the same stratigraphic position contain *Scaphites* cf. *ventricosus* Meek & Hayden, *Ostrea congesta* Conrad and *Anomia subquadrata* Stanton. However, this horizon, that is, the uppermost part of the Platy Shale zone, is known to contain, farther north, both *S. ventricosus* and *B. ovatus*. It marks the intermingling of the waning Upper Colorado types and the new early Montana forms. The few specimens of *I. lundbreckensis* collected by the writers in Ghost River area and farther northwest are from the Upper Concretionary zone, associated with the *B. ovatus* fauna. As McLearn has suggested, *I. lundbreckensis* is affiliated with the Montana, rather than the Colorado, fauna. It is unfortunate that, to the writers' knowledge, *B. ovatus* itself, which is generally regarded as an index of Montana age, has not yet been found in the Crowsnest River and adjacent areas.

CORRELATIONS

The fossil zones established in the Alberta shale, that is, the "Benton" of the Alberta foothills, are roughly equivalent to similar zones within the Colorado formation of northern Montana and the central Great Plains region, and in the Colorado and lowest Montana formations in the Rocky Mountain region from southern Montana to New Mexico.

The close resemblance of several of the species to European forms, and at least two instances of specific identity, furnish the basis for the correlation of the Alberta shale with the Turonian and Lower Senonian of the standard European section.

Barren zone.—The faunal list from this zone includes two identified species, *Inoceramus corpulentus* McLearn and *Acanthoceras albertense* Warren, also *Prionotropis* and *Ichthyodectes*, the species of which are unknown. None of this material forms a safe basis for a direct correlation, except within the Alberta foothills.

Warren (33) lists *A. albertense* Warren from the basal part of the Kaskapau shale (Lower Smoky River shale), in the Peace River area. It occurs between the base of the *I. labiatus* zone and the top of the Dunvegan formation. This evidence points to the equivalence of at least the lowermost beds of the Kaskapau shale to the Barren zone in the base of the Blackstone formation. Incidentally, it also indicates a probable correlation of the upper Blairmore beds with the Dunvegan formation. As already noted, a large ammonite, resembling *A. albertense*, occurs in the Barren zone about 50 feet above the top of the Blairmore formation on Castle River, at the south end of the region.

Reeside (24) records *Acanthoceras* from the lower Graneros (basal Benton) shale of eastern Colorado, and states that it occurs at this horizon in several other areas in the United States. It is possible that the *Acanthoceras* fauna is older than Lower Turonian in age. The correlation is at present uncertain, but these basal beds may yet prove to be late Cenomanian in age.

In the San Juan basin of Colorado and New Mexico, according to Reeside (22) the basal Mancos shale is barren of fossil evidence. Mention is made of a fauna which occurs in stratigraphically equivalent beds in other areas in the western United States, containing *Metoicoceras whitei* Hyatt, *Gryphea newberryi* Stanton, and *Exogyra columbella* Meek. This *Metoicoceras* fauna, however, is consistently at a higher horizon than the *Acanthoceras* fauna, and in association with the *Inoceramus labiatus* fauna, therefore definitely Lower Turonian in age.

The lower part of the Thermopolis shale of southern Montana and Wyoming (21) occupies a stratigraphic position equivalent to that of the Barren zone, but lack of fossils in the former beds precludes a direct correlation. In northern Montana, general stratigraphic relationships indicate that the equivalent of the Barren zone may exist in the upper part of the Blackleaf Sandy member of the Colorado formation.

Inoceramus labiatus zone.—This zone is characterized by the abundance of *Inoceramus labiatus* Schlotheim with a few *Prionotropis woolgari* Mantell. Warren and Rutherford (32) have made a questionable determination of *P. hyatti* also.

As previously stated, the collections obtained by the present writers, further substantiated by core-drilling data obtained in the southern foothills, indicate that *P. woolgari* occurs within the range of *I. labiatus* and does not mark a higher, separate zone.

Ostrea congesta Conrad has been found in these beds, but is not common nor diagnostic as it occurs abundantly much higher in the group.

The *I. labiatus* fauna is present in the Peace River region in the lower 350 feet of the Kaskapau shale, according to McLearn (19) and Rutherford and Warren (27). *Prionotropis* is there associated in occurrence with *I. labiatus*.

In northern Montana (4), *I. labiatus* Schlotheim is definitely recognized in one zone only, between 1,000 and 1,100 feet below the top of the Colorado shale, that is, just above the top of the Blackleaf Sandy member of the Colorado. It is well known in the Mosby sandstone which occurs in this part of the section. Farther north, in the southern Alberta plains region, the senior author recognized this fossil zone, in the same stratigraphic position, in cores from a well drilled at Taber, Alberta. Both *Inoceramus* cf. *labiatus* and *Prionotropis* cf. *woolgari* are present in fine-grained, black, fissile shale.

In southern Montana, *I. labiatus* marks a restricted zone, and in Wyoming this fauna occurs in the Frontier formation only. On the east, in the central Great Plains region, it is confined to the Greenhorn limestone. In the San Juan basin of Colorado and New Mexico, the *I. labiatus* fauna is found in the lower part of the Mancos shale.

The work of Reeside has indicated three distinct fossil zones which are very persistent in the lower Colorado of the western United States. These zones are listed in descending order.

1. *Scaphites warreni zone.*—Associated with *S. warreni* Meek and Hayden are *Prionotropis hyatti* and *Prionocyclus wyomingensis*. This fauna marks the Upper Carlile shale.

2. *Prionotropis woolgari zone.*—Associated with *P. woolgari* are *Scaphites larvaeformis* and *Inoceramus fragilus*. The last-named species ranges upward into the *S. warreni* zone also. The *P. woolgari* fauna is an index to the Lower Carlile shale.

3. *Inoceramus labiatus zone.*—*I. labiatus* Schlotheim is abundant in this zone. *Prionotropis* occurs, but it is a different species from either *P. hyatti* or *P. woolgari*, which, so far, have not been found in association with *I. labiatus* in the United States.

The S. warreni fauna, according to the work of Warren and Rutherford (32) and the writers, has not been found in the Alberta shales. *S. warreni* seems to be absent, and a questionable *P. hyatti* was determined by Warren, in association with *I. labiatus*. Warren and Rutherford state that *P. woolgari* marks a zone above the *I. labiatus* zone in the Alberta foothills, but, as already indicated, the work done by the present writers does not confirm this zoning.

The beds included in the *I. labiatus* zone in Alberta are considered the equivalents of strata at least as low as the base of the Frontier formation, or the base of the Greenhorn limestone, and, possibly, as high as the top of the Carlile shale of the western United States.

The world-wide distribution of *I. labiatus* Schlotheim is well-known. Heinz (9, 10) states that this species occurs in the Lower Turonian of Europe, Asia, Africa, and America. The *I. labiatus* zone of Alberta may therefore be referred to this part of the standard European column.

Scaphites ventricosus zone.—Warren and Rutherford fully discuss the fauna and correlation of this zone and point out that the Cardium formation lies within the range of *Scaphites ventricosus* and does not represent a true fossil zone. *Cardium pauperculum* Meek is abundant in this formation at some localities, but is not restricted in its vertical range. This species is reported by Johnson (14) as present in the Carlile shale and *C.* cf. *pauperculum* is reported by Collier (4) from the top of the Colorado in northern Montana.

The *Scaphites ventricosus* fauna is present in the Peace River area in the Bad Heart sandstone and in the underlying uppermost 200 feet of the Kaskapau shale, according to McLearn (19) and Rutherford and Warren (26).

Scaphites ventricosus Meek and Hayden, in northern Montana, (4) ranges from a horizon between 650 and 750 feet below the top of the Colorado upward to the top of this formation. It is associated with several species of *Inoceramus* and *Baculites* commonly found in the *S. ventricosus* zone in Alberta. *Ostrea congesta* Conrad is also abundant in this zone and is common to both regions.

Reeside (21) reports a large number of the species generally associated with *S. ventricosus* from the Niobrara shale of southern Montana. The Niobrara fauna of the Mancos shale in the San Juan basin (22) includes the following species in common with the *S. ventricosus* zone of the Alberta shale:—*S. ventricosus* Meek and Hayden, *S. vermiformis* Meek and Hayden, *Baculites asper* Morton and *B.* cf. *codyensis* Reeside. These species, with the associated fauna found in the Alberta shale, form a good basis for correlation of the

strata of the *S. ventricosus* zone with that part of the Mancos shale containing the Niobrara fauna.

The faunal list of the *S. ventricosus* zone contains a large number of different species of the genus *Inoceramus*. Schluter (28) states that *Inoceramus* is represented in the "Emscher-Mergel" of Germany (equivalent to Coniacian, that is, Upper Colorado) by a large number of diversified species, and that the genus reached the acme of its development in that stage.

Stanton (30) has pointed out that certain of the species of the Colorado fauna are represented by similar groups in the Emscherian, for example: *Inoceramus exogyroides* Meek and Hayden and *Inoceramus umbonatus* Meek and Hayden are represented by *Inoceramus involutus* Sowerby; *Inoceramus deformis* Meek by *Inoceramus cuvieri* Sowerby; *Baculites asper* Morton by *Baculites incurvatus* Dujardin. Schluter (28) recognized *I. exogyroides* and *I. umbonatus* as occurring in the "Emscher-Mergel," and Heine (8) records *I. umbonatus* from the *I. involutus* zone in the Lower Emscherian of Germany. According to Heinz (10), *Inoceramus flaccidus* White occurs in the Lower Emscherian of Europe and America. He also reports (9, 10) *I. deformis* Meek from the Upper Turonian of Germany. In the United States this species is strictly lower Niobrara in aspect in the entire interior region, and lower Austin or equivalents in the Texas coastal plain. *I. deformis* is definitely post-Turonian in its associations in North America.

It is interesting to note that in western Alberta, on the basis of the present collections, *I. deformis* is limited in range to the lower part of the *S. ventricosus* zone and has been used by the writers as an index to this horizon. It ranges no lower than *S. ventricosus* and seems to be confined to this lower Niobrara, or Lower Emscherian, horizon.

It may be stated, then, that the European equivalent of the *S. ventricosus* zone of western Alberta is found, generally, in the Emscherian (Coniacian), which is considered by some geologists as intermediate between the Turonian and Senonian, but is most commonly placed in the Lower Senonian.

Baculites ovatus zone.—Warren and Rutherford (32) named this zone from the common occurrence of *Baculites ovatus* Say, which, throughout most of the region, ranges from about 600 feet below the top of the Wapiabi upward in the section to within a few feet of the Wapiabi-Belly River contact. This species is most widely distributed in the upper half of the Upper Concretionary Shale zone, which occupies most of this interval. The absence of *B. ovatus* itself, in the

southern foothills, has already been mentioned; in that part of the region, however, *Inoceramus lundbreckensis* McLearn, which is one of the elements of the *B. ovatus* fauna, appears to be diagnostic of the uppermost Wapiabi shales.

In other parts of southern Alberta and the western United States *Baculites ovatus* Say ranges upward into strata of much later Montana age than the *B. ovatus* zone of the Alberta foothills.

In northern Alberta this fauna is present in the Upper Smoky River shale of the Peace River area (19, 26) and probably in the middle part of the Labiche shale of the Athabaska River area.

In southern Montana, Reeside (21) records *Baculites ovatus* Say from the upper part of the Telegraph Creek formation and the overlying Eagle sandstone. The occurrences of the species *Desmoscaphites bassleri* Reeside and *Baculites aquilaensis* var. *haresi* Reeside in the Alberta collections seem to indicate an affinity with the Telegraph Creek fauna rather than the Eagle. Also, as shown by Warren and Rutherford (32), the species *Scaphites hippocrepis* Dekay, which is prominent in the Eagle fauna, has not yet been found in the *Baculites ovatus* zone of the Alberta foothills.

It is interesting to record the occurrence of a large *Nautilus*, resembling *Eutrephoceras alcesense* Reeside, from the upper part of this zone. Reeside (23) reports this species from the Eagle sandstone, Montana, the Telegraph Creek formation, Montana, the upper part of the Cody shale, Wyoming, the Steele shale, central Wyoming, the uppermost part of the Mancos shale, eastern central Utah, and the uppermost Mancos and basal Mesaverde formations of the upper Rio Grande region, New Mexico.

Although the *B. ovatus* fauna contains a number of species which occur in the Colorado group, as a whole it appears to have more affinities with the fauna of the lower part of the Montana group.

Reeside has indicated that the Telegraph Creek fauna can be correlated with the *Santonian* division of the middle Upper Cretaceous. For the present, the writers are inclined to accept this conclusion and to consider the *Baculites ovatus* zone as approximately equivalent to that part of the European stratigraphic column.

CONCLUSIONS

1. The formations established by Malloch (18) in the Bighorn coal basin, namely, the Blackstone shales, Bighorn formation, and Wapiabi shales, are equivalent in every respect to the Lower Benton, Cardium and Upper Benton formations described by Rutherford (26) for the Bow River area.

2. There are many objections to the use of the terms "Benton" or "Colorado" as either formation or group names in Alberta. The introduction of the name Alberta shale by Hume (13) fills the need for a group term which must include strata of both Colorado and Montana age. It is proposed that Malloch's nomenclature be retained for the lower and upper formations of the group, that is, the Blackstone and Wapiabi, respectively; Lower Benton and Upper Benton should be discarded as formation names. On the other hand, it is believed that Cardium should supplant Bighorn in naming the middle formation of the group.

3. The Blackstone, Cardium, and Wapiabi formations are readily recognizable units throughout the region herein discussed, which extends for 350 miles along the foothills belt of southwestern Alberta. Northwestward from Bow River each formation maintains a nearly uniform thickness; southeastward from the Bow, the Blackstone and Cardium formations diminish in thickness, and the sandstone members of the Cardium become erratic in their distribution.

4. The senior writer found it practicable and convenient to divide each of the three formations into zones or members on the basis of lithologic differences which are easily discernible in the field. These zones were extremely useful in mapping and for correlation purposes, because they are, for the most part, persistent throughout the region under discussion. Important changes occur in the lithologic character of the Cardium formation and the upper beds of the Wapiabi formation south of Bow River.

5. The fossil zones discussed are, in general, the same as those described by Warren and Rutherford (32) and McLearn (20), except with regard to the stratigraphic significance of *Prionotropis woolgari*. The present writers find that this species occurs in the *Inoceramus labiatus* zone and does not range any higher than the latter species; *P. woolgari*, therefore, is not herein regarded as diagnostic of a zone above the *I. labiatus* zone. The fossil zones recognized are the Barren zone, the *Inoceramus labiatus* zone, the *Scaphites ventricosus* zone, and the *Baculites ovatus* zone.

6. The Blackstone formation is Lower Colorado, that is, Turonian in age. The basal part may yet prove to be Cenomanian in age. The Cardium and the lower part of the Wapiabi are of Upper Colorado age, which is the homotaxial equivalent of the Emscherian (Coniacian) division of the Lower Senonian of Europe. The uppermost part of the Wapiabi formation is early Montana in age and may be correlated with the Santonian division of the Lower Senonian.

7. The change from marine sediments of Colorado age to marine

sediments of Montana age appears to be entirely gradational, and intermingling of the Montana type fossil, *Baculites ovatus*, with typical Upper Colorado forms has been noted in strata at the top of the Platy Shale zone in the Wapiabi formation.

8. The "Benton" group, or Alberta shale, of the Alberta foothills includes the Blackstone, Cardium, and Wapiabi formations, and is approximately equivalent to the Colorado, group, plus the lowest beds of the Montana group, as known in the central Great Plains and Rocky Mountain regions of the United States.

REFERENCES

1. J. A. Allan (and R. L. Rutherford), "Saunders Creek and Nordegg Coal Basins," *Sci. and Ind. Research Council* (University of Alberta, Edmonton) *Rept. 6* (1922).

2. ——— (and R. L. Rutherford), "Geology along the Blackstone, Brazeau and Pembina Rivers in the Foothills Belt, Alberta, *ibid. Rept. 9* (1924).

3. D. D. Cairnes, "Moose Mountain District, Southern Alberta," *Geol. Survey Canada Mem. 61* (1914).

4. A. J. Collier, "The Kevin-Sunburst Oil Field and Other Possibilities of Oil and Gas in the Sweetgrass Arch, Montana," *U.S. Geol. Survey Bull. 812-B* (1929).

5. N. H. Darton, "Geology of the Bighorn Mountains," *ibid., Prof. Paper 51* (1906).

6. C. S. Evans, "Some Stratigraphic Sections in the Foothill Region, between Bow and North Saskatchewan Rivers, Alberta," *Geol. Survey Canada Summ. Rept.*, Pt. B (1929).

7. Dr. Hector, *Report of the Palliser Expedition*, 1859.

8. F. Heine, "Die Inoceramen des Mittelwestfälischen Emschers und unteren Untersenons," *Abh. der Preuss. Geol. Landesanstalt*, Neue Folge, Heft 120 (1929).

9. R. Heinz, "Das Inoceramen-Profil der Oberen Kreide Lüneburgs. Mit Anführung der neuen Formen und deren Kennzeichnung. Beiträge zur Kenntnis der oberkretazischen Inoceramen. I.," *Einundzwanzigster Jahresbericht des Niedersächsischen geologischen Vereins* (1928).

10. ———, "Über die bisher wenig beachtete Skulptur der Inoceramen-Schale und ihre stratigraphische Bedeutung. Beiträge zur Kenntnis der oberkretazischen Inoceramen. IV," *Mitteilungen aus dem Min. Geol. Staatsinstitut in Hamburg*, Heft 10 (1928).

11. G. S. Hume, "Turner Valley Oil Area, Alberta," *Geol. Survey Canada, Summ. Rept.*, Pt. B (1926).

12. ———, "Oil Prospects near Bragg Creek, Alberta," *ibid.* (1927).

13. ———, "The Highwood-Jumping Pound Anticline, with Notes on Turner Valley, New Black Diamond, and Priddis Valley Structures, Alberta," *ibid.* (1929).

14. J. H. Johnson, "The Benton Fauna of Eastern Colorado and Kansas and its Recorded Geologic Range," *Jour. Paleon.*, Vol. 4, No. 2 (1930).

15. B. R. MacKay, "Brule Mines Coal Area, Alberta," *Geol. Survey Canada, Summ. Rept.*, Pt. B. 1928.

16. ———, "Stratigraphy and Structure of Bituminous Coal Fields in the Vicinity of Jasper Park, Alberta," *Canadian Min. Met. Bull. 213* (January, 1930).

17. J. MacVicar, "Preliminary Investigation of Coal Deposits on Smoky, Hay, and Berland Rivers, Alberta," *Geol. Survey Canada Summ. Rept.*, Pt. B. (1923).

18. G. S. Malloch, "Bighorn Coal Basin, Alberta," *ibid., Mem. 9-E* (1911).

19. F. H. McLearn, "New Species from the Coloradoan of Lower Smoky and Lower Peace Rivers, Alberta," *ibid., Bull. 42* (1926).

20. ——— (with S. S. Buckman and E. W. Berry), "Mesozoic Palaeontology of Blairmore Region, Alberta: Stratigraphic Palaeontology," *ibid., Bull, 58* (1929).

21. J. B. Reeside, "A New Fauna from the Colorado group of Southern Montana," *U.S. Geol. Survey Prof. Paper 132 B* (1923).

22. ———, "Upper Cretaceous and Tertiary formations of the Western Part of the San Juan Basin, Colorado, and New Mexico," *ibid., Prof. Paper 134* (1924).

23. ———, "The Cephalopods of the Eagle Sandstone and Related Formations in the Western Interior of the United States," *ibid., Prof. Paper 151* (1927).

24. ———, Acanthoceras Fauna from Eastern Colorado," *Jour. Washington Acad Sci.*, Vol. 17 (1927), p. 453.

25. R. L. Rutherford, "Geology of the Foothills Belt between McLeod and Athabaska Rivers, Alberta," *Sci. and Ind. Research Council* (Univ. of Alberta, Edmonton), *Rept. 11* (1925).

26. ———, "Geology along the Bow River between Cochrane and Kananaskis, Alberta," *ibid., Rept. 19* (1928).

27. ——— (and P. S. Warren), "Geology and Water Resources in Parts of the Peace River and Grande Prairie Districts, Alberta," *ibid., Rept. 21* (1930).

28. C. Schlüter, *Paleontographica*, Bd. 24 (1877). Separate, p. 35.

29. S. E. Slipper, "Sheep River Gas and Oil Field, Alberta," *Geol. Survey Canada Mem. 122* (1921).

30. T. W. Stanton, "The Colorado Formation and its Invertebrate Fauna," *U.S. Geol. Survey Bull. 106* (1893).

31. J. S. Stewart, "Geology of the Disturbed Belt of Southwestern Alberta," *Geol. Survey Canada Mem. 112* (1919).

32. P. S. Warren (and R. L. Rutherford), "Fossil Zones in the Colorado Shale of Alberta," *Amer. Jour. Sci.*, Ser. 5, Vol. 16, No. 92 (1928).

33. ———, "Three New Ammonites from the Cretaceous of Alberta," *Trans. Roy. Soc. Canada*, 3d. Ser., Vol. 24, Sec. 4 (1930).

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 11 (NOVEMBER, 1934), PP. 1417-1453. 8 FIGS.

STRUCTURE OF TURNER VALLEY GAS AND OIL FIELD, ALBERTA[1]

THEODORE A. LINK[2]
Calgary, Alberta

P. D. MOORE[3]
San Angelo, Texas

ABSTRACT

Turner Valley is structurally probably the most complicated oil field in North America. It is a highly folded and faulted compound anticlinal overthrust sheet bordering the outer Foothills Belt of Alberta. It involves Paleozoic limestones, dolomites, and shales, Jurassic shale, and Cretaceous rocks. From the surface, the structure appears to be rather simple, with apparently uninterrupted east and west rim rocks of Belly River sandstone enclosing Colorado shale. The major overthrust fault, which underlies part or all of the structure, is of considerable magnitude and appears to be warped. A high-gravity naphtha is produced with large volumes of gas from a dolomitized zone in the Paleozoic limestone, whereas small amounts of high-gravity crude are obtained from Mesozoic sandstones at shallower depths. No connate water has been encountered in either the limestone or the upper producing sands. The heavier oils are found in the youngest formations and show a progressive decrease in gravity with depth.

This paper consists of a discussion of the salient structural features, including two structure-contour maps, seven cross sections, an abridged geologic column, production statistics, and several photographs.

INTRODUCTION

A reasonable interpretation of the structure of the Turner Valley gas and oil field had to be preceded by the compilation of a detailed and accurate stratigraphic column. The stratigraphy of the Turner Valley field, as accepted to-day, is almost wholly the accomplishment of the junior writer. During the time of greatest activity in the field new stratigraphic information derived from studies of well cuttings was coming in so fast, and ideas were revised so often, that there seemed to be no time for considered opinion on structural problems. Each new well appeared as a contradiction to the latest stratigraphic and structural interpretation. In addition, the deviation from the vertical of many of the bore-holes made such data of doubtful value. It seemed better practice to postpone a structural map until other

[1] Presented by title before the association at the Dallas meeting, March 24, 1934. Manuscript received, May 18, 1934. Published by permission of O. B. Hopkins, chief geologist, Imperial Oil, Ltd., Toronto, Ontario.

[2] Geologist in charge, Imperial Oil, Ltd.

[3] Consulting geologist. Formerly resident geologist at Turner Valley, for Imperial Oil, Ltd.

wells in a critical part of the field should supply more important data. Except in the extreme south end, no new wells are being located at the present writing. In the extreme northern end (near the Model wells), more data would be very welcome, but the prospects for such data in the immediate future appear doubtful.

The structural interpretation of Turner Valley has passed through several stages since the time Dowling's first report and map appeared in 1915.[4] The conception of a major sole fault underlying the valley was essentially established in the year 1928, when British Dominion No. 1 encountered Belly River or younger beds after drilling 5,480 feet of Colorado shale on the east flank of the structure. Space does not permit the tracing of the structural and stratigraphic interpretations of the valley. The reader may find considerable on this subject in the bibliography of this paper, but unfortunately the entire story is not to be found in print. Complete records of the many arguments, the countless cross sections drawn and discarded, and the scores of hypotheses thrown overboard during the last few years would fill many pages. Preconceived notions and orthodox theories had to be abandoned in many instances. In spite of the considerable number of data available at present, there are many unsolved problems, and there is a considerable area within the valley proper where structure contours are merely conjectural. The nature of the closely drilled areas is taken into consideration when extending contour lines into undrilled areas with the understanding that future drilling may alter the hypothetical secondary structures.

The writers are fully aware of the fact that several interpretations are feasible with the data at hand. Likewise they feel that previous experience will influence, to a considerable extent, the method of using the data and building up the contour maps and cross sections. In applying the interpretations presented in this contribution, the senior writer has been influenced by his extensive field experience in the Foothills Belt, where the "regional habit"[5] has been impressed most forcibly upon him. The results of the experimental studies performed by the senior writer[6] have also influenced, to a marked degree, specific interpretations. Last, but not least, informal discussion with other workers has played an important part in the final analysis. Three geophysical parties have worked in the valley—electrical (resistivity),

[4] D. B. Dowling, "Geological Notes to Accompany Map of Sheep River Gas and Oil Field, Alberta," *Geol. Survey of Canada Mem. 52* (1914), Geol. Ser. 42.

[5] B. F. Hake, Discussion of A. J. Goodman's paper, *Canada Min. & Met. Bull. 233* (September, 1931), pp. 1103–05.

[6] Theo. A. Link, "Three-Dimensional Experiments in Earth Deformation," *University of Chicago Science Ser.*, Vol. V (1926–27), abstract of thesis.

seismic refraction, and seismic reflection. None of these methods gave tangible results. Aerial photographs aided considerably in defining the formation boundaries. The "grain" of the Turner Valley structure, as portrayed on the structure contour maps of this paper, is very similar in appearance to areal maps covering larger portions of the Foothills Belt of Alberta, chosen at random. The writers believe that essentially all geologists familiar with foothills conditions will find no fundamental objections to the maps and cross sections as submitted herewith, but naturally differences of opinion regarding details and theoretical points are expected.

ABRIDGED STATISTICS FOR TURNER VALLEY—ALBERTA

Number of holes drilled (completed or uncompleted)	178
Average depth of all holes drilled (completed or uncompleted)	4,389 feet
Number of holes drilled into Paleozoic limestone	101
Number of producing wells drilled into limestone	95
Number of holes being drilled or deepened Feb. 1st, 1934	15
Average depth of all holes drilled into limestone	5,272 feet
Average depth to top of limestone	4,798 feet
Deepest hole drilled (McLeod No. 4)	7,751 feet
Average approximate cost of drilling producing well into limestone	$175,000.00
Length of producing field	14 miles
Average width of field	1½ miles
Amount of acreage in proved area (approximate)	11,200 acres
Average production of naphtha per well (under present conditions, January 1, 1934)	39 bbl. per day
Average production of natural gas per well (under present conditions, January 1, 1934)	3,546,500 cu. ft. per day
Total production of naphtha to January 1, 1934	6,483,667 bbl.
Total production of crude oil to January 1, 1934	377,388 bbl.
*Total production of natural gas to January 1, 1934	604,729,004,000 cu. ft.
Initial "closed-in" pressure (estimated)	2,000 to 2,100 lbs.
Recent "closed-in" pressure	535 to 1,690 lbs., September 8, 1933
Gas-oil ratio	41.8 M.C.F. per bbl. in 1926 130.0 M.C.F. per bbl. in 1932
Gravity of naphtha	Gravity A.P.I.—73.6° Bé.
Discovery date of limestone production (in Royalite #4)	Oct. 20, 1924
Location of field	T. 18–20, R. 2–3, W. of the 5th M. Central part lies in Lat. 50° 40′ N.—Long. 114° 16′ (41 miles SW. of Calgary, Alberta by auto road)

* Figure obtained from provincial government. Others estimate as low as 400,000 M.C.F.

SOURCE OF DATA

In studying the structure of the Turner Valley field it is essential not only to consider the subsurface well-log data, but also to have a first-hand knowledge of all the surface exposures. The major, as well as some of the secondary structural features, are expressed in some

of the surface exposures. However, the data from surface information was not sufficiently obvious to enable the pioneer workers to arrive at a true picture of the folding in the limestone, the existence of the major sole fault, and the presence of the numerous minor folds and faults within the Cretaceous formations. The authors feel convinced that a first-hand knowledge of both the subsurface and surface data is essential before any attempt at interpreting the structure of Turner Valley is made. In a paper of this nature, it is impossible to reproduce the maze of detail collected from surface exposures, as well as that detected in the well logs, and the reader will have to assume the stratigraphic interpretations as correct, and the surface mapping as complete. All stream traverses were run by plane-table on a scale of 12 inches to the mile, while the ridges were mapped on a scale of 4 inches to the mile.

DEVIATION OF BORE-HOLES

In constructing the various cross sections and contour maps, the deviation of the bore-holes from the vertical gave rise to considerable trouble. This was overcome, for the most part, by first ignoring the records of those wells deviating excessively. After completion of the structure-contour map, these wells were considered and, in several cases where directional surveys were available, it was found that migration *up the dip* is a common habit of rotary drilled holes above the 3,500 foot depth. This was usually confirmed by the well log which in these cases shows a minimum of section between two given horizons. Some of the apparent smoothness of structure at the top of the limestone may be due to ignoring this up-dip migration in wells where there are no data on the subject. There are a few cases where migration with the rotary was down the dip in softer material lying above a hard stratum or between two harder beds both dipping at an extremely high angle (60° or more). Deviations as high as 25° from the vertical were recorded by acid-bottle surveys in one of the cable-tool wells. One of the rotary holes showed a horizontal drift of 1,200 feet in a depth of only 5,084 feet, and practically all of this deviation was above the 3,500-foot level. The latter was surveyed by a Sperry-Sun gyroscopic machine. Deviation from the vertical in *cable-tool holes* appears to have been *down the dip* in all instances in Turner Valley.

STRATIGRAPHY

For the purposes of this paper there is no need of introducing details regarding the stratigraphic column of Turner Valley. However, all available details had to be utilized and were absolutely essential in interpreting each well log, and in the placing of the various faults or

overturned beds. The stratigraphic column on the maps gives enough data to show which are the relatively competent and incompetent beds of the column, their thickness and relative positions. For more detailed information on this subject the reader is referred to Moore's[7] paper.

TOPOGRAPHIC EXPRESSION OF TURNER VALLEY STRUCTURE

The excellent section through the central part of the Turner Valley structure, as exposed along Sheep River, and the well developed east and west rim-rock ridges, are quite misleading as to what may be expected beneath the surface. The east Belly River rim rock is continuous throughout the entire length of the structure except in two stretches south of Sheep River, where two river or fluvio-glacial terraces mantle the bevelled ridges. The north as well as the south plunges of the structure are easily recognized from the topography as half bowl-shaped recesses. Though appearing as a topographic extension of the main structure, the extreme northern end is structurally related to the "Millarville overthrust sheet," to be described later.

The west Belly River rim rock is not a continuous ridge, because it is cut by several longitudinal or sub-parallel faults. On some of the previously published maps, *transverse faults* were introduced to explain several *en échelon* offsets along the western rim. The results of drilling, and the study of numerous other Foothills structures indicate that transverse faults are extremely rare, if present at all. The west rim rock consists of a series of *en échelon* Belly River sandstone ridges cut by sub-parallel, longitudinal faults, which in places are overlapped by the "Outwest overthrust sheet," as shown on the maps. It is highly probable that some of these faults represent a branching of the Millarville sole fault, as indicated in Figure 1.

The surface trace of the major overthrust fault is a matter of uncertainty. There is no definite topographic expression of this large fault, and regarding it Goodman[8] states:

> The disturbance where the sole fault is said to outcrop near the Sentinel well is the merest pucker at surface. It is clearly a fault of small throw, for it is difficult to imagine how the beds of the upper fault-block have come to rest after travelling an appreciable distance in such a way that they should match so well with those of the lower fault-block. . . . Does the true fault outcrop then lie more to the east?

[7] P. D. Moore, "Stratigraphy of the Turner Valley Field." Manuscript.

Note—For a complete list of all wells drilled in Turner Valley in which are given the most important horizon markers, oil and gas horizons, etc., see *Schedule of Oil and Gas Wells*, Dept. of Lands and Mines, Petroleum and Natural Gas Division, Province of Alberta. Price $2.50, plus postage. Edmonton, Alberta.

[8] A. G. Goodman, "The Structure of Turner Valley Gas Field, Alberta," *Canada Min. & Met. Bull. 224* (December, 1930), pp. 1507 and 1508.

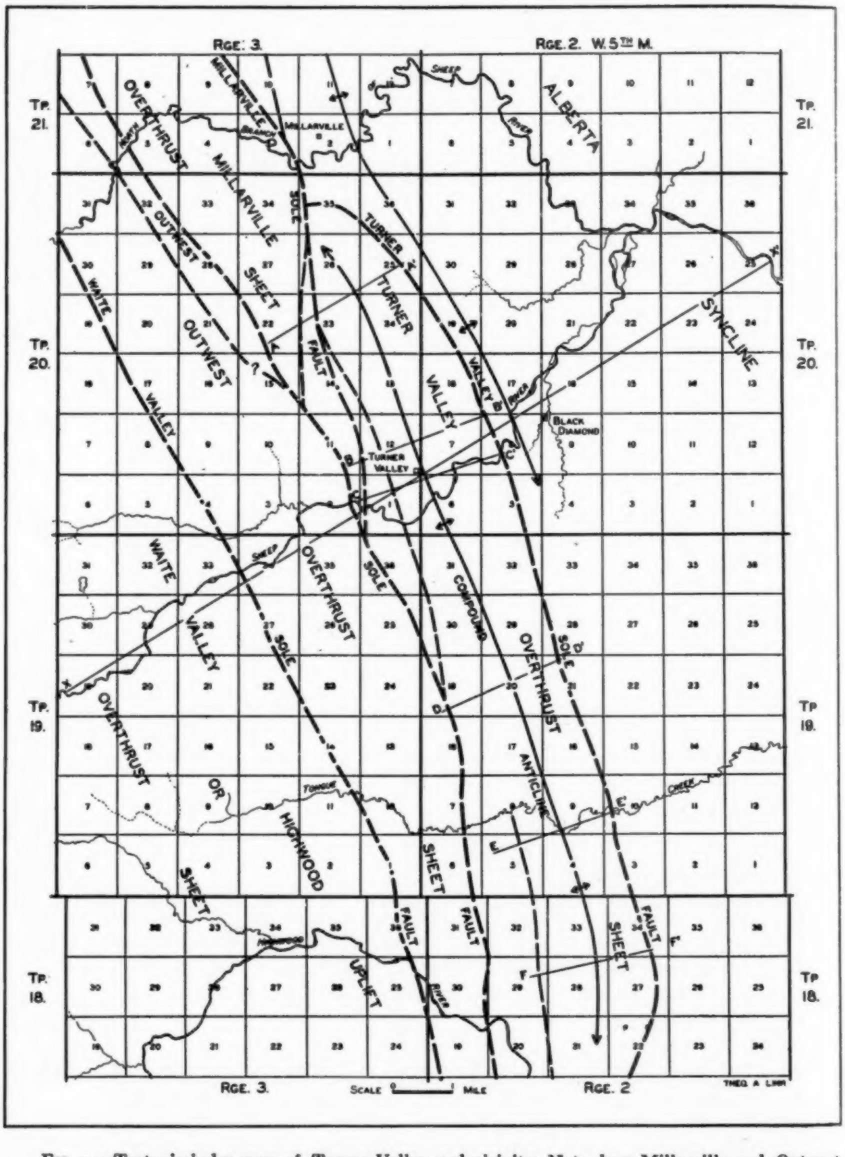


FIG. 1.—Tectonic index map of Turner Valley and vicinity. Note how Millarville and Outwest overthrust sheets overlap Turner Valley sheet. Position of cross section illustrated in Figure 2 shown by line X-X'. Cross sections A–A' to F–F' are illustrated in Figures 3 and 4.

As will be pointed out later, Goodman did not have the necessary data regarding the sole fault at the time his article was written. G. S. Hume[9] places the surface outcrop of the sole fault about 500 feet west of the Sentinel well, where a tight fold (as referred to by Goodman) is exposed in Edmonton beds. The authors place the surface trace at, and in line with, the abandoned Black Diamond (McPherson) coal mines, about 2,400 feet west of the Sentinel well. Information from several men acquainted with the old coal mines workings leads to this conclusion. According to their story the coal was intensely folded, faulted, and pitching at a high angle. The footwall was "highly polished." Many other Foothills faults are definitely related to Kootenay and Belly River coal seams, as pointed out later. As indicated in the cross sections, the major sole fault is regarded as branching near the Sentinel well.

DEFINITION OF TURNER VALLEY STRUCTURE

The Turner Valley structure is a highly faulted, closely folded, anticlinal fold, bounded on the east by a major overthrust sole fault which underlies the entire structure or the greater part of it. On the west this structure is bounded by one or two similar overthrust sheets. The north end of Turner Valley is merely an *apparent* or physiographic continuation of Turner Valley proper. It is one of the westerly overthrust sheets cutting obliquely across the northward plunge of the main structure. This extreme north end of the valley has been termed the "Millarville overthrust sheet." An examination of the maps, as well as the cross sections, brings out this relationship clearly and also shows how the "Outwest overthrust sheet" overlaps both the main Turner Valley structure and the "Millarville overthrust sheet." The formations lying directly beneath the major Turner Valley sole fault are also highly faulted and as closely folded as the valley structure itself.

It appears that the Paleozoic limestone of Turner Valley has no connection with that of the Outwest sheet lying directly west of the valley, nor with the Highwood-Waite Valley uplift. It seems highly probable that the Turner Valley limestone fold is a subsurface island or decapitated fold of limestone torn from its base or roots in the manner indicated in the cross section (Fig. 2).

MAJOR SOLE FAULT

The writers do not regard the Turner Valley structure as a true *nappe* in the sense of being a recumbent anticline, the reverse limb of

[9] G. S. Hume, "Turner Valley Sheet Map No. 257-A," *Geol. Survey of Canada Pub.* 2252 (1931).

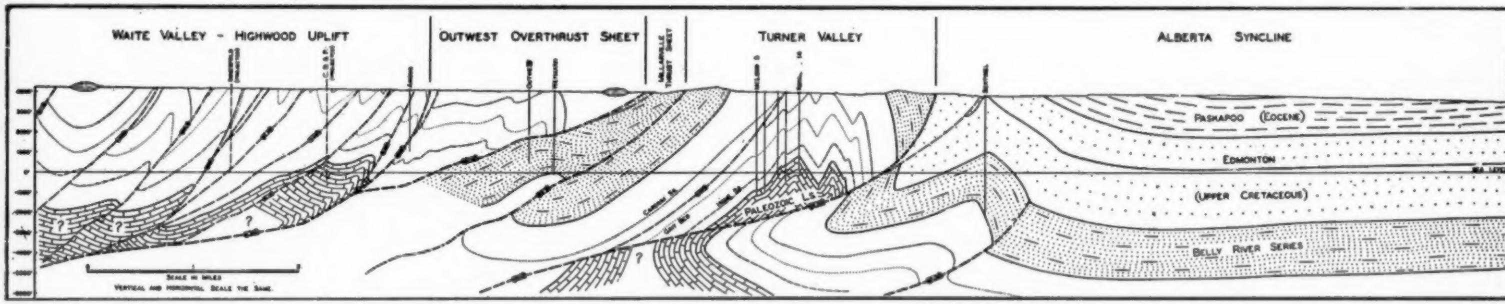


FIG. 2.—Cross section along Sheep River showing relationship of Turner Valley, Inner Foothills, and Alberta syncline. Truncated limestone fold or "roots" from which Turner Valley limestone was torn may lie farther west than indicated in this cross section. Note several overthrust sheets and warping or folding of major sole faults.

which has partly disappeared owing to stretching. The manner in which the limestone is supposed to have been torn from its roots is slightly different from that postulated for the Alpine *nappes*. No excessive stretching of the reverse limb appears to have taken place. On the contrary, the limestone mass appears to be the crest of a previously developed fold which was truncated or sheared off along a thrust fault emerging from the west, and carried eastward for a considerable but unknown distance. The age of the truncated fold is not to be regarded as belonging to a previous period of folding. It merely antedates the advancing thrust fault growing at depth from the west and advancing eastward during the same orogenic movement. The data clearly indicate a thrust sheet of great displacement which has glided over a fault plane or zone dipping very gently westward, directly beneath the limestone, but emerging at a high angle at the surface. It is probable that the Belly River coal seam lying east of the valley acted as a gliding plane or lubricant at that level. Throughout the Foothills area there is a tendency of the major sole faults to glide, for considerable distances, along the coal seams. This does not imply that the faults follow the seams regardless of inclination, but that wherever an overthrust fault, growing from the west at depth, encountered a coal series or seam, that horizon would be chosen only so long as the nature of the stresses causing the displacement and the attitude of the coal seam allowed such adjustment. Such gliding planes are common in the Kootenay as well as in the Belly River coal series. The Outwest fault, which overlaps the western rim rock of Turner Valley (see maps) is also found to emerge along Sheep River in the Belly River coal seams.

EVIDENCE SUPPORTING PRESENCE OF MAJOR SOLE FAULT

The presence of a large overthrust fault in Turner Valley has been a matter of considerable discussion. In the early publications[10] on this area, the magnitude of such a fault lying on the east, and extending below the valley, was not discussed because of lack of subsurface data. After the year 1924, when drilling activities became more intense, speculations as to the presence and nature of an overthrust fault became rife. There is no need of following the history of this controversy, but the following data establish, beyond a doubt, the existence of a west-dipping and possibly warped or folded overthrust sole fault.

At British Dominion No. 1 in L.S. 4, Sec. 5, T. 20, R. 2, West of

[10] S. E. Slipper, *Geol. Survey of Canada Mem. 122* (1919).
D. B. Dowling, *Geol. Survey of Canada Mem. 52* (1913).

the 5th,[11] drilling commenced in the Upper Colorado shale. The Cardium sandstone was encountered at 2,910 feet and again at 3,610 feet (the latter time inverted). At a depth of 5,480 feet the drill passed from Colorado shale into Belly River or younger formations and continued in the latter to the 6,525-foot mark. The hole was abandoned in July, 1930.

A re-examination of the samples from the old Great West No. 1 hole in L.S. 2, Sec. 7, T. 20, R. 2, revealed a condition similar to that encountered in British Dominion No. 1. The Cardium sandstone was encountered at a depth of 1,480 feet, and again at 3,860 feet (inverted). At the 5,010-foot level the drill passed from Upper Colorado into Belly River or younger beds (cross section *C–C′*). It is in place here to call attention to the fact that this hole was abandoned in 1927. Thus the data establishing the presence of the fault was at hand, but the Belly River beds encountered in this hole had been interpreted at that time as Blairmore (Dakota of earlier authors).

At Mill City No. 1 in L.S. 14, Sec. 4, T. 19, R. 2, the drill passed from Paleozoic limestone through the fault into Colorado or younger beds at a depth of 5,010 feet.

At Sterling Pacific No. 1 in L.S. 15, Sec. 33, T. 18, R. 2, the drill passed from Paleozoic limestone into Belly River or Blairmore beds at a depth of 6,436 feet. This hole migrated eastward toward the fault. It is in place to remark here that several rotary-drilled wells, located on the east flank, migrated westward into the structure and reached the productive zone in the limestone without encountering the major fault. This would not have been the case if the holes had been drilled perfectly straight.

At Mercury No. 5 in L.S. 2, Sec. 4, T. 19, R. 2, the major sole fault was encountered at a depth of 5,660 feet, when the drill passed from Fernie shale into the Colorado shale. In the north end of the field, United No. 4 (in L.S. 2, Sec. 24, T. 20, R. 3) encountered the fault at a depth of 6,325 feet. At this location the drill passed from the Paleozoic limestone back into the Fernie shale at the 6,055-foot mark. Here the beds were found to be inverted. From the Fernie the drill passed through the fault into the Colorado shale at the depth of 6,325 feet. This condition is obviously due to a drag on the upthrown side of the sole fault.

At Dome No. 1 (in L.S. 2, Sec. 24, T. 20, R. 3) near United No. 4, the major fault was encountered by passing from middle Blairmore back into Lower Colorado at a depth of 5,840 feet.

[11] Note: Hereafter all legal descriptions are regarded as west of the 5th Meridian.

At Foothills No. 4 in L.S. 1, Sec. 26, T. 20, R. 3, the drill penetrated 4,530 feet of Colorado shale and was abandoned at that depth under the assumption that it would have encountered the major fault if carried deeper. This is the most northerly hole serving to locate the subsurface trace of the major sole fault.

The most southerly location is the Hoffar-Lundy No. 1 in L.S. 13, Sec. 22, T. 18, R. 2, where the Cardium sandstone was reached at the 3,100-foot and again at the 3,470-foot depths. Drilling ceased at 4,280 feet in Colorado shale. This location has been temporarily abandoned under the assumption that the drill was in the drag of the upthrown side and that the major fault zone would shortly be encountered. Drilling may be resumed at this location in the near future.

McLeod No. 4, in L.S. 16, Sec. 1, T. 20, R. 3, is not only the deepest hole in the Turner Valley field (7,751 feet), but also the most important in establishing the magnitude and nature of the major overthrust fault. This well is located *west* of the main high in the central part of the field. The top of the Paleozoic limestone was reached at a depth of 3,720 feet. At 5,870 the drill passed from Banff shales (Paleozoic) through a fault into Fernie shales; at 5,963 from Fernie into Blairmore, and at 6,012 from inverted Blairmore into inverted Colorado shale. The Cardium sandstone (inverted) was passed through near the 6,300-foot mark, and encountered again in normal position at 7,735. Drilling was abandoned at a depth of 7,751 feet. These data show conclusively that the major sole fault is not everywhere one single smooth plane, but consists of a zone of faults. The principal gliding plane appears to be the one at 5,963 feet. The tremendous drag on the downthrown side is clearly demonstrated by the position of the Cardium sandstone inverted at the 6,300-foot level and in normal position at the 7,735-foot level (cross section *C–C′*). In all cases where cores were taken below the major fault, high dips were observed to be prevalent in the strata below the fault plane.

The fault plane or zone appears to be quite irregular and possibly folded. The elevation at which the fault was encountered at the wells cited is here shown.

Well	*Side of Structure*	*Feet Below Sea-Level*
United 4	East	2,013
Dome 1	East	1,616
Great West 1	East	1,107
McLeod 4	West	1,956
British Dominion 1	East	1,495
Mill City 1	East	985
Mercury 5	East	1,492
Sterling Pacific 1	East	2,222

These figures show a considerable range of elevation of the fault plane. Obviously the locations on the far east side should strike the plane at a shallower depth than those farther west, but the significant point is the fact that McLeod 4, on the west flank of the structure, encountered the fault higher than United 4 and Sterling Pacific No. 1. (The latter hole deviated considerably from the vertical, and the fault may lie 200–400 feet higher than indicated in the above figures.) These locations are not on the same cross section, but the extremely low-angle westward dip of the fault plane is well established, with undulations possibly caused by subsequent folding. The data obtained in the McLeod well No. 4 indicate quite clearly that the displacement along the major fault is of the first order. Goodman's[12] statement, "The disturbance where the sole fault is said to outcrop near the Sentinel Well is the merest pucker at surface," is another example of nature's success in hiding, or rather disguising, its secrets.

The trace of the major sole fault is shown as swinging around both the north and south plunge of the Turner Valley structure. At the north end the sole fault is indicated as passing beneath the "Millarville overthrust sheet." Hume[13] and others believe that the Turner Valley sole fault continues more or less along the same trend beyond the northern plunge of the structure, but the results at Foothills No. 4, in L.S. 1, Sec. 26, T. 20, R. 3, are highly suggestive of a bend in the fault trace as indicated on the maps. Furthermore, the results of experiments performed by the writer lead him to believe that the Turner Valley structure is arcuate and that the underlying sole fault has the same tendency to swing sharply around the north and south ends in harmony with the anticlinal structure itself. At the south end of the valley this swing of the major fault is more definitely established by an excellent section of exposures on Highwood River. The gentle eastward dips in the Edmonton and younger beds continue upstream to a point on the boundary line between Sections 9 and 10 in T. 18, R. 2. At that location there is an abrupt demarkation between closely folded and highly faulted Bearpaw shales with up-folded Belly River and down-folded Edmonton sandstones and the gentle east dips referred to. The major sole fault of Turner Valley must pass through that location or west thereof. This alone is regarded as conclusive evidence upon which to place a decided swing of the surface trace of the fault on the maps. The important results of the Hoffar-Lundy test

[12] A. J. Goodman, "The Structure of Turner Valley Gas-Field, Alberta," *Canada Inst. Min. & Met. Bull. 224* (December, 1930), p. 1507.

[13] G. S. Hume, "Overthrust Faulting and Oil Bearing Prospects, etc." *Econ. Geol.* Vol. XXVI, No. 3, (May, 1931), p. 261. In this contribution Hume states that the fault extends "for 40 miles."

well (L.S. 13, Sec. 22, T. 18, R. 2) already indicate the subsurface swing of the fault. Prospects for the definite delineation of this fault at the extreme south end of the valley are very bright, since several locations have been made close to the danger line. Their results are awaited with interest. There is the possibility that the large fault is split up into several minor ones at the south end, or that it dies out entirely.

STRUCTURE-CONTOUR MAPS

GENERAL

In preparing the structure-contour maps based upon the two different datum planes, the Cardium sandstone and the top of the Paleozoic limestone (Figs. 3 and 4) it was found necessary to do this work in conjunction with the preparation of 31 cross sections, only 6 of which are submitted in this paper. Inversely, it was found impossible to draw reasonable cross sections without corresponding or complementary contour maps. In other words, the projection of individual wells onto cross sections was found impossible if the strike of the beds was not known. Without structure-contour maps the projection of wells gave rise to hopeless confusion and illogical interpretation of structural features in cross section. This same interrelationship also had to be obtained between the structure-contour maps prepared on the different datum planes, only two of which are submitted in this paper. It was found possible, for example, to prepare a fairly logical contour map with the top of the Paleozoic limestone as datum, but when a similar map on the "Home sand" was prepared, it was found necessary to alter both of the maps so that they might conform to each other and to the available data. Needless to say, this proved to be an almost endless task. The original contour maps were prepared on a scale of 4 inches to the mile with a contour interval of 100 feet.

SECONDARY STRUCTURES

The structure-contour maps on the two horizon- or datum-planes selected show only a reasonable similarity. However, it is quite apparent that a structural high at the surface does not necessarily indicate its presence or position at depth in the Paleozoic limestone. In the central part of the field, where Sheep Creek cuts across the structure, excellent outcrops indicate the presence of two very distinct asymmetrical anticlines flanked by the Cardium sandstone. There is also evidence of other minor folds or faults. Two of these secondary structures are apparently maintained from the Cardium sandstone down to the limestone in accordance with the dip of their axial planes.

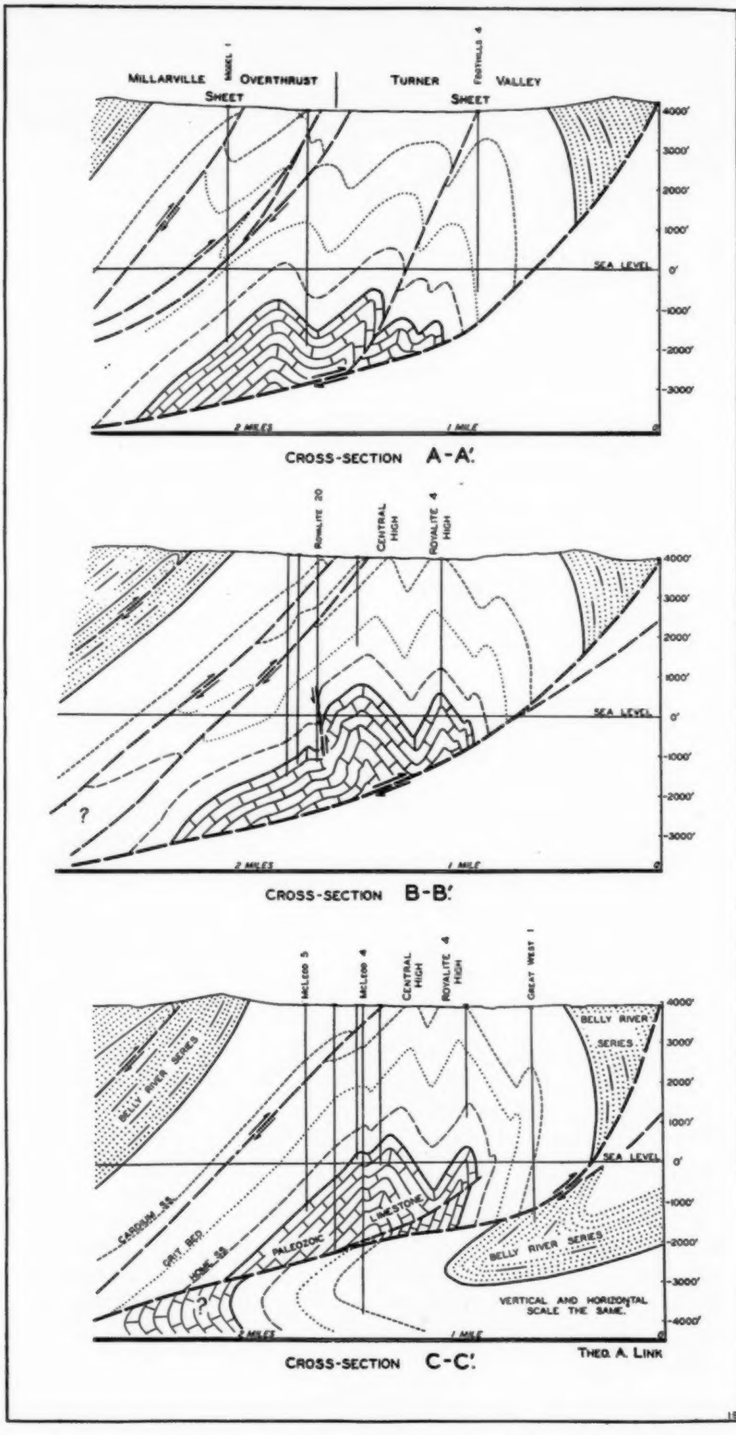


FIG. 3.—Cross sections A–A' to C–C' through north half of Turner Valley overthrust sheet. With one exception, no wells are projected but all lie directly on line of cross sections. Note how Model well and Foothills well No. 1 begin in Millarville overthrust sheet and end in Turner Valley sheet (section A–A').

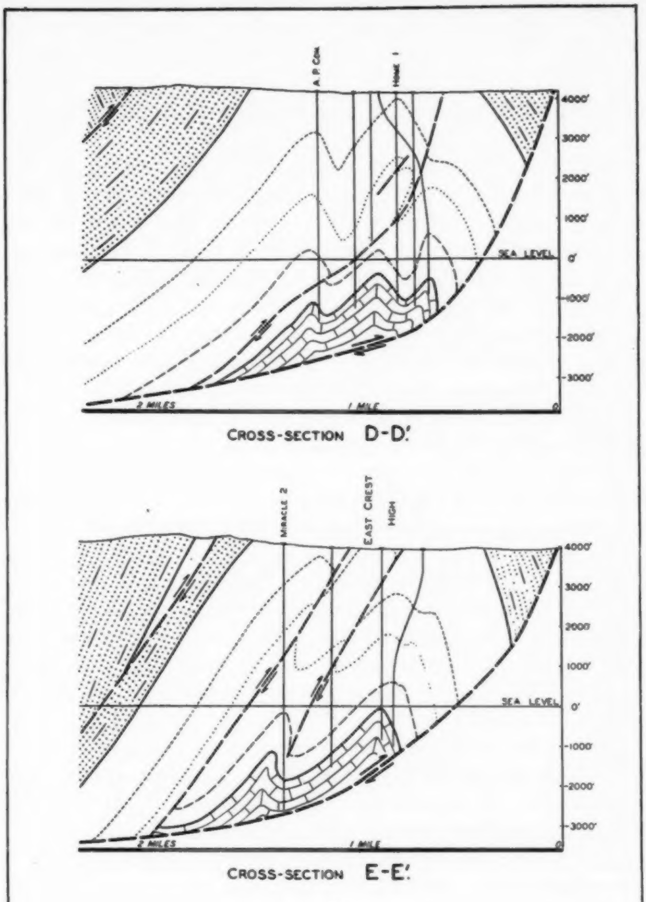


FIG. 4.—Cross sections *D–D'* to *F–F'* through south half of Turner Valley overthrust sheet. For position of cross sections see index map (Fig. 1). Note deviation from vertical in several wells, and simpler type of structure in extreme south end (section *F–F'*).

The structures under consideration are the "Royalite Four high" and the "Central high." Cross sections through these structures show a close correspondence between the top of the limestone, the Home sand, the Grit bed and the Cardium sandstone. However, on the west flank of the "Central high," the Cardium sandstone is cut into two sheets pushed over the main fold along low-angle fault planes. The presence of secondary high-angle thrust faults, as formerly interpreted by the writers[14] and also indicated in Hume's[15] cross section, seems doubtful. After thorough consideration and many trials in making maps and cross sections, the writers believe that the lower-angle faults within the Colorado shales fit the facts more closely than the high-angle faults do. These medium-angle secondary faults also eliminate postulating excessive flowage within the Colorado shale, and resemble the major fault on a smaller scale. Another change in interpretation is the omitting of an underthrust fault between the "Central" and "Royalite Four" highs. This altered interpretation is based on a re-examination of the cuttings from the Royalite wells Nos. 1, 2, and 3. It is possible that such an underthrust does exist, but the evidence is not conclusive. There is no doubt that the Royalite well No. 1 deviates considerably from the vertical, as suggested by Slipper[16] in 1921.

The behavior of the Grit bed in the Home group (Sec. 20, T. 19, R. 2) is somewhat complicated and gave rise to almost utter confusion in drawing up the sections and maps (cross section *D–D′*). The excessive migration of the rotary-drilled holes in that area adds to the confusion, and the writers are fully aware of the fact that alternative interpretations are possible. Directional surveys of all the holes in this group would throw considerable light on the subject.

Due to the several sheets of Cardium and Lower Colorado shale thrust over one another along relatively low-angle faults on the "Central high," it is impossible to draw up one structure-contour map on this datum plane showing the true conditions. With use of transparent sheets this can be done. However, the cross sections (*B–B′* and *C–C′*) bring out the relationship quite clearly and show that on the main structure-contour map of the Cardium sandstone, the contours on the down-thrown Cardium sandstone are drawn westward to the

[14] Sidney Powers, "Cross-Section of Turner Valley by P. D. Moore and T. A. Link," *A.I.M.E. Tech. Pub. 377*, Pet. Div. 37 (1931), p. 42.

[15] G. S. Hume, "Structure and Oil Prospects of the Eastern Foothills Area, Alberta, between Highwood and Bow Rivers," *The Engineering Journal of Canada* (January, 1931), Fig. 3-p.

[16] S. E. Slipper, "Sheep River Gas and Oil Field, Alberta," *Mem. 122, Geol. Series 104* (1921), Fig. 4, p. 22.

point or line where the overlying fault cuts the down-thrown portion of the Cardium sandstone. From that line westward the contour lines on the next overlying sheet are shown, et cetera. This method does not reveal the true maximum displacement of the faults on the structure-contour map, and the cross sections should be consulted for that information.

REGIONAL STRUCTURAL RELATIONSHIP AND ACCUMULATION OF GAS AND OIL

The relationship between Turner Valley and the regional structure is a matter of importance with respect to the accumulation of gas, oil, and naphtha. The Turner Valley structure is one of the "outer" or most easterly folds of the Foothills Belt exposing the Colorado shale. As illustrated in Figures 1 and 2, another fold lies east of Turner Valley, but the lowest formations exposed on its crest are sandstone and shale members of the Edmonton. The Sentinel well No. 1 (L.S. 15, Sec. 8, T. 20, R. 2) was drilled to a depth of 5,800 feet on the crest of this most easterly fold and was still drilling in Belly River beds when operations were suspended. If this hole could be deepened to 10,000 feet or more, very important data would be forthcoming. It is very doubtful that the Paleozoic limestone would be encountered *before* such depths are reached.[17]

Due to the underlying sole fault of Turner Valley, it is probable that the accumulation of oil, gas, or water has very little relationship with the Alberta syncline on the east. Since the Paleozoic limestone on the downthrown side of the Turner Valley sole fault is overlain by a great thickness of younger beds, and is apparently disconnected from the limestone on the upthrown side, the conception of large-scale migration from the east seems improbable, if not impossible. As previously pointed out,[18] the asymmetry of the Alberta syncline precludes such a possibility.

West of Turner Valley several wells have been drilled into the Paleozoic limestone. One of these in particular is of great importance because it lies directly behind Turner Valley on the nearest uplift on which the limestone was encountered. The well in question is the Calgary Development and Producers, Ltd. No. 1 in Waite Valley, located in L.S. 10, Sec. 21, T. 20, R. 3, W. of the 5th (elevation 4,604 feet). The limestone was encountered at a depth of 4,150 feet (454 feet above sea-level), and after obtaining small showings of oil in the upper part

[17] Theodore A. Link, "The Alberta Syncline, Canada," *Bull. Amer. Assoc. Petrol. Geol.* Vol. 15. No. 5 (1931), p. 500.

[18] *Op. cit.*, pp. 504–7 and Fig. 3.

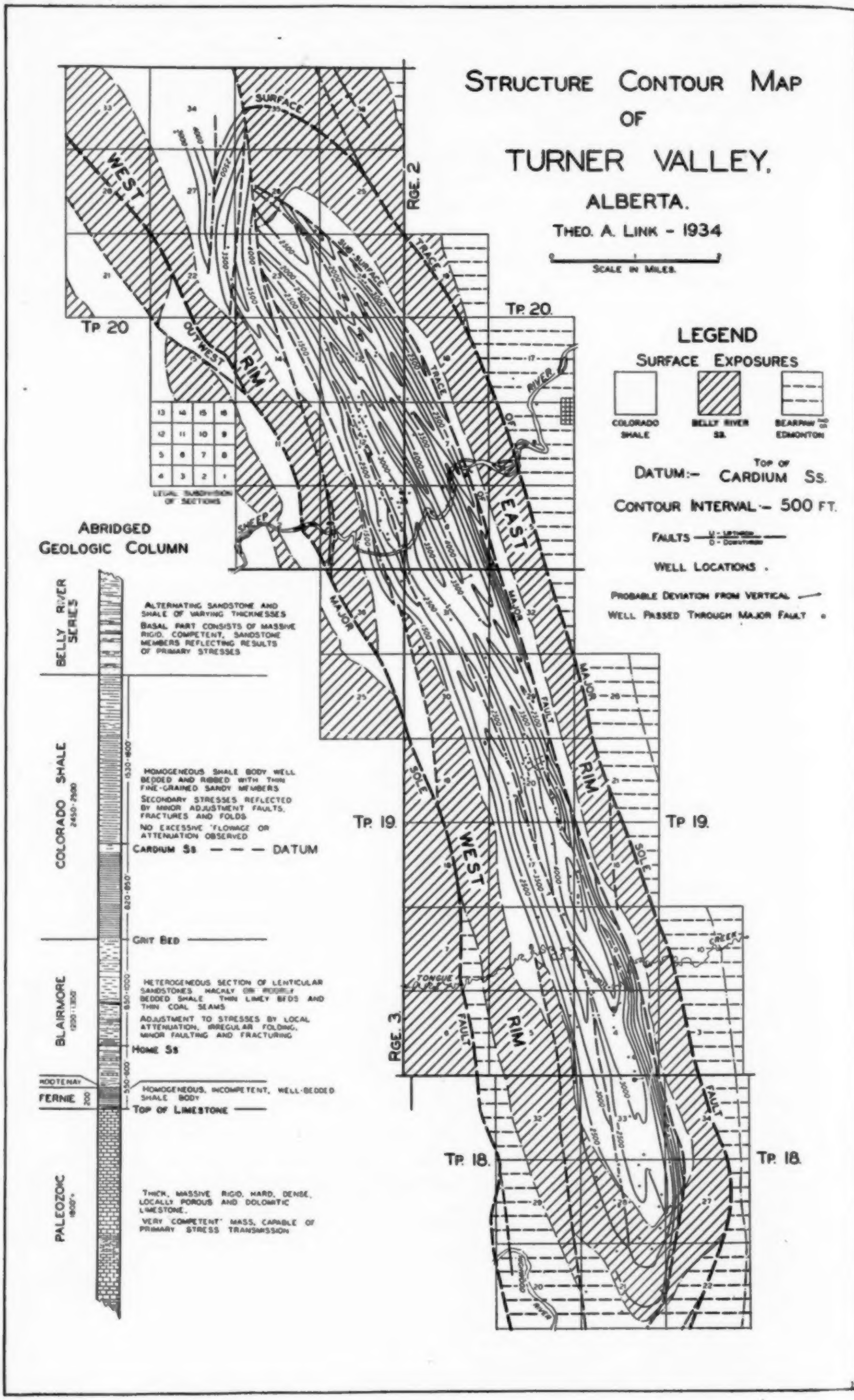


Fig. 5.—Structure-contour map of Turner Valley on Cardium sandstone as datum, with abridged geologic column.

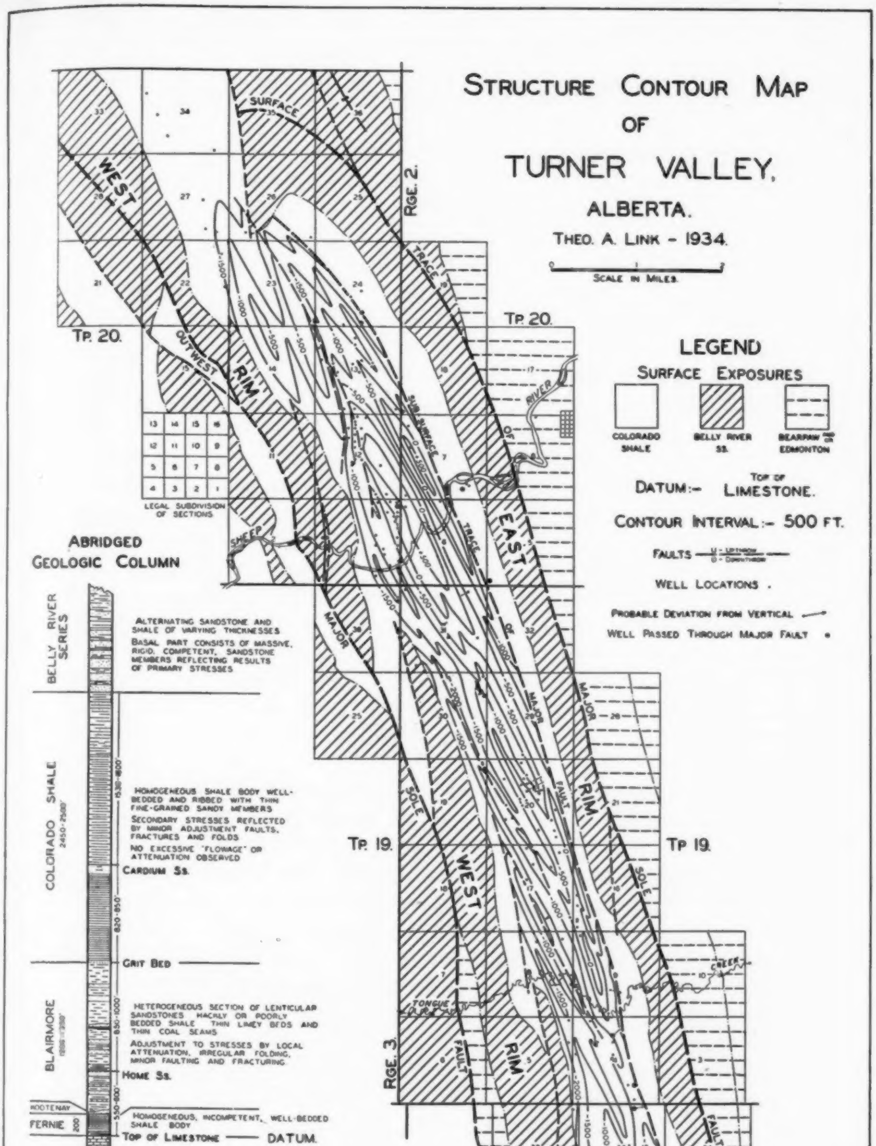


FIG. 6.—Structure-contour map of Turner Valley on top of Paleozoic limestone as datum, with abridged geologic column.

of the limestone, a large quantity of sulphur water was encountered at 4,450 to 4,510 feet, or 154 feet above sea-level (Fig. 2). This column of water rose to a height of 1,900 feet above sea-level, which is higher by 1300 feet than any part of the limestone in Turner Valley. Similar flows of water were encountered in *all other wells* which reached the limestone on the Highwood uplift west of Turner Valley. The afore-mentioned C.D. & P. well No. 1 encountered the limestone on the Waite Valley-Highwood overthrust sheet which disconnects the Paleozoic limestone from the Turner Valley overthrust sheet just as the latter is disconnected from the Alberta syncline. In fact the Outwest overthrust sheet, which probably involves no Paleozoic limestone, lies between Turner Valley and this location.

In Turner Valley there has been no considerable amount of water encountered in any part of the limestone. This applies to all wells, even those far down the flank of the structure. If the Turner Valley Paleozoic limestone is connected directly or indirectly with the limestone of the Highwood overthrust sheet, one might reasonably expect this hydrostatic head to exert its influence in the Valley. One might reason, however, that the confined gas pressure of Turner Valley holds the water level far down the flank below the hydrostatic level of the C.D. & P. well, and that as the rock pressure declines in Turner Valley the water will eventually encroach and flood the limestone. At present this seems improbable, because all of the wells have already shown a considerable decline in rock pressure, in gas volume, and the gas-oil ratio, with no definite or unquestionable encroaching of flank water. If the rock pressure of Turner Valley were, in part, due to the hydrostatic head from the west, one would expect the loss of volume in gas to be accompanied by encroachment of water in considerable amounts much greater than the water which is found in several of the wells at the present time. Furthermore, the rock pressure is not the same throughout the field, and its decline is also variable. If the hydrostatic head were the controlling factor in the rock pressure, the decline in pressure should be more uniform than it is. After considering all the data available at present, it appears quite reasonable to conclude that the Paleozoic limestone of Turner Valley is disconnected not only from that of the Alberta syncline on the east, but also from the limestone on the west in the Highwood or Outwest overthrust sheet, and that the high rock pressure of the valley is due to a confinement of the gas in this huge block of folded and faulted limestone. There is no doubt that water is also present in the Turner Valley overthrust sheet of limestone, and that all of the wells will eventually show water as some do now, but not in amounts as great as would be ex-

pected if the Turner Valley thrust sheet were connected with the limestone lying on the west or the east.

Assuming this structural interpretation to be correct, it is of interest to consider the time and place of the generation, migration, and accumulation of the hydrocarbons in Turner Valley. Migration from younger beds into the limestone subsequent to the movement along the major sole fault seems to be out of the question in view of the barren nature of the Cretaceous beds below the major fault. The oil and gas encountered in the Mesozoic sands in Turner Valley are free from sulphur and appear to be unrelated to that in the limestone. The gravity decreases downward, which is the opposite of so-called normal conditions. If generation of hydrocarbons took place within the upper Paleozoic limestone or the Fernie shales (the two probable source horizons), it is possible that this may have occurred after the movements along the major fault planes. However, it is also possible that generation and migration of hydrocarbons may have preceded the major structural movements and that after the Turner Valley limestone sheet became disconnected from the adjoining masses, additional compression caused further generation of greater pressure and the formation of the more volatile hydrocarbons characteristic of Turner Valley. This latter possibility seems the most probable in view of the stratigraphic data collected by the junior author, which points to a pre-Fernie high in the Paleozoic limestone. If this is true, it seems highly probable that the generation of hydrocarbons was also fairly well localized, and that migration before the major movements was also limited. This is suggested by the lack of large quantities of gas in the limestone of the Highwood uplift on the west. At any rate, the failure to find gas or oil in large quantities in other foothills structures but, instead, the finding of large amounts of sulphur water, leads one to the conclusion that the Turner Valley overthrust sheet is an unusual combination of oil migration and structural conditions in the Foothills. This does not imply that other fields may not be discovered, but emphasizes the fact that no definite criteria are available to enable one to make positive statements. Another interesting feature of the Turner Valley limestone production is the fact that the sulphur content of the gas shows a progressive increase from 200 grains in the north end to 960 grains per 100 cubic feet in the extreme south end. The writers have no explanation to offer for this problem.

LOCAL ACCUMULATION WITHIN TURNER VALLEY

Initial production from the porous zone varies considerably in Turner Valley, very small non-commercial production has been en-

countered in many wells, while one of the richest producers (Home No. 1) showed an initial volume of 21 million cubic feet of gas per day capable of producing about 900 barrels of naphtha. Some of the wells came in with a very low gas-oil ratio, while others were dry from the beginning. There seems to be no definite structural relationship capable of accounting for such diversity of production both in amount and quality. The highest well structurally (Royalite No. 14) produced a large volume of some of the driest gas, while many of the low flanking wells, such as Model No. 1, Foothills No. 1, Miracle No. 2 and Advance 5 produce extremely wet gas and lower gravity naphtha. There are, however, notable exceptions to this rule, but space will not permit their enumeration. The porous zone is apparently not the only pre-requisite for a commercial producer.

Fracturing of the porous zone appears to have played a very important rôle in determining the volume of gas produced from the wells. "Shooting" with nitro-glycerine has increased the production of some wells, while others have received no benefits from a "shot." Treating the porous dolomite with hot acid might increase production in some of the depleted low-pressure areas. All the large producers were characterized by the great amounts of fragmental dolomite blown out during their early history. The porosity of such fragments was nowhere any greater than that obtained in the smaller and non-commercial wells.

In closely drilled areas, the production was rarely increased materially after a certain number of wells had been completed. This is particularly true of the "Home area" where the last holes to be completed turned out financial losses. On the other hand, Royalite No. 4, which was for several years one of the only two wells drilled into production on the "Royalite Four high," stands out as the one convincing argument that Turner Valley was over-drilled in most instances. This well produced from 1924 to 1931 approximately 36,000 million cubic feet of gas from which were extracted slightly less than one million barrels of crude naphtha. Two or three wells within a radius of 300 feet would probably have produced very little more over the same period of years.

OROGENIC HISTORY OF TURNER VALLEY STRUCTURE

In the cross section (Fig. 2) an attempt is made to show the relationship of the "Inner" Foothills, Turner Valley, and the Alberta syncline. Space does not permit a full discussion of that subject, since the Foothills of Alberta show a great diversity of structural types. Not all of these types are found on this particular cross section. Stated

as briefly as possible, the Foothills type of structure embodies certain characteristics of the Alpine nappes, the Jura folds (which glided over a plane lubricated by underlying salt), and the Scottish Highland structures cut by many slice faults. The cross section (Fig. 2) shows large low-angle major sole faults, which bear evidence of having been

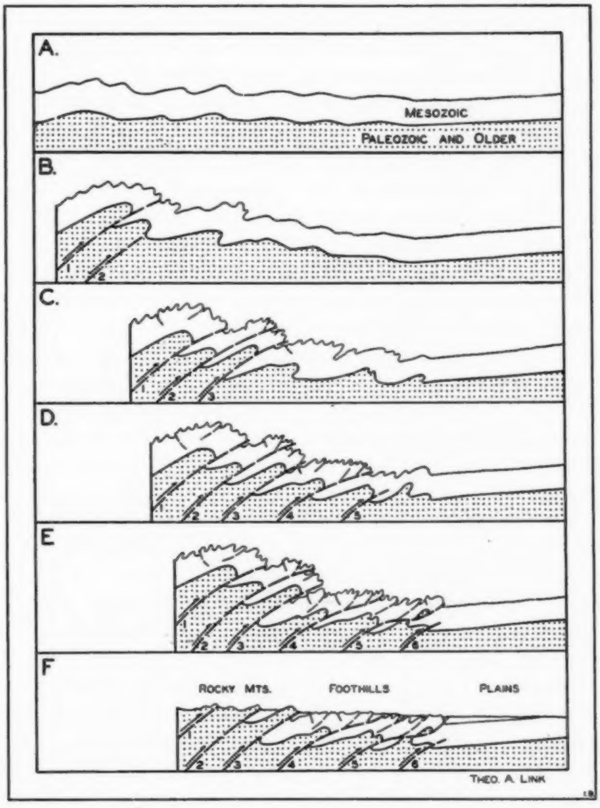


Fig. 7.—Illustrating orogenic history of eastern Rocky Mountains and Foothills.
Stage A represents initial period of gentle folds.
Stage B shows growth of first overthrust faults from west.
Stage C further development of overthrust faults from west to east, showing intense folding and minor adjustment faulting in less competent Mesozoic rocks.
Stage D continued development of disturbed belt eastwardly.
Stage E shows truncation of limestone fold by low-angle overthrust fault as postulated for Turner Valley.
Stage F Same as *E* after erosion to present levels. (Erosion was continuous from *A* to *F*.) Consecutive development of major faults indicated by numbers 1–6.

folded. This is particularly the case closer to the Rocky Mountains. It is highly probable that some of these sole faults have also been cut by later slice faults.

High-angle slice faults also are present, while underthrusting and underfolding are common phenomena. Many of the inner Foothills folds show, in the competent Belly River series, that the west flank is steeper than the east side, which suggests undertucking after movement along the major fault had ceased. West-dipping thrust fault blocks or sheets are more common than folds like Turner Valley. The former are almost invariably cut by high-angle slice faults. Practically all minor adjustments appear to have been accomplished by faulting rather than by excessive flowage. Although the surface trace of the Alberta syncline lies several miles east of the outer fold of the Foothills, the axial plane dips toward the west so that, at depth, this axis underlies the most easterly portion of the Foothills.[19]

The orogenic history of the Rocky Mountains and Foothills of Alberta has been presented by several investigators, but the majority of them have given most attention to the Mountains, with secondary thought to the Foothills.[19] The sequence of events during the orogenesis which gave rise to the Foothills structure is interpreted by the writers in the following summary, which deals only with the period and method of orogenic movement. For a brief review of the sedimentary history the reader is referred to previous contributions on that subject.[20]

The tectonic forces which caused the building of the Rocky Mountains and the Foothills originated west of the Cordilleran geosyncline and were active from west to east. The first results of these forces were the formation of parallel folds similar to the more simple types of Appalachian folds. As the stresses grew more intense, faulting developed in the most westerly and deeper lying zone. These displacements originated in the competent and deeply buried pre-Cambrian and Paleozoic sediments. The folding of the Paleozoic and older sediments gave rise to simpler types than in the Mesozoic and Tertiary section, and stresses were relieved by faulting primarily as observed in the eastern ranges of the Rocky Mountains.

[19] J. D. MacKenzie, "The Historical and Structural Geology of the Southernmost Rocky Mountains of Canada," *Trans. Roy. Soc. Canada*, Vol. 16, Ser. 3, Sec. 4 (1922).

C. S. Evans, "Brisco-Dogtooth Map Area, British Columbia," *Geol. Survey of Canada Summary Rept. 1932*, Pt. A.2, pp. 106A–76A.

[20] Theodore A. Link, "The Alberta Syncline, Alberta," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 5 (May, 1931), pp. 493–95.

P. D. Moore, "Some Aspects of the Sub-Surface Geology of Alberta," *Stanford University, California, Micropaleontology Bull.*, Vol. 3, No. 4 (December, 1932).

The emergence of these faults from the competent Paleozoic section into the overlying Mesozoic sediments caused a decrease in the angle of their dip, and in many cases gliding took place along Kootenay and Belly River coal seams, as was the case along parts of the Outwest and Turner Valley sole faults.

As the compressive forces continued, the width of disturbed sediments was gradually increased eastward. Tightly compressed folds and numerous minor adjustment faults were developed in the younger, less competent rocks. Since the major overthrust faults originated at depth in the western border of the geosyncline, displacements along them decrease toward the east and some of them die out as folds before the surface is reached. An example of such a fault is the one shown below the Turner Valley sheet and ending in the "Sentinel fold" (Fig. 2). The amount of displacement along these major sole faults is obviously limited by friction along the gliding plane. When friction has become so great that no more displacement can take place, adjustments to the stresses must be made along more newly developed planes. These, according to experimental data,[21] would develop farther eastward at depth, below the just abandoned plane of adjustment. However, before any great dislocation takes place along a newly developed major fault plane, other means of adjustment are in operation on the upthrown side of the previously developed thrust sheet. Slice faults, underthrusts and undertucking of the west flank of the fold takes place prior to and during the inception of a newly formed major sole fault at depth. This undertucking of the west flank appears to be a common feature in the Foothills and probably represents the last stages of adjustment on the upthrown side of the major faults. It is also accompanied by a warping or folding of the large faults, and in some cases, a dislocation by minor slice faults. Obviously, such intensely deformed segments are more common in the Inner Foothills Belt, where the stresses were more intense and operative over a longer period. There are numerous examples of very low-angle gliding planes, many of which followed the Kootenay coal series in the Inner Foothills Belt in and far from the Turner Valley district. Hume[22] concluded that the large Lewis overthrust, at Waterton Lakes in the mountains, is folded. In the same contribution he also records major fault planes (such as the Lewis) following Kootenay coal beds.

[21] Theodore A. Link, "Relationship between Over- and Underthrusting as Revealed by Experiments," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12, No. 8 (August, 1928), pp. 831–33.

[22] G. S. Hume, "Waterton Lakes—Flathead Area, Alberta and British Columbia," *Geol. Survey of Canada Summary Rept.*, Pt. B (1932), pp. 8B–9B.

FIG. 8.—General view of central part of Turner Valley gas and oil field, Alberta, looking northwest. Sheep River at extreme left, Rocky Mountains form left sky-line. West Belly River rim rock forms central and right sky-line. Royalite Oil Company absorption plant at left and scrubbing plant at right. (Photo by W. J. Oliver, Calgary, Alberta.)

Since the Turner Valley overthrust sheet is one of the last to be developed in the orogenic history of the Foothills, the amount of warping or folding of the major fault plane is not of considerable extent directly below Turner Valley. There is no doubt, however, that the fault plane is much more folded, and possibly re-faulted farther westward. The cross section (Fig. 2) was drawn up under the most conservative hypothesis with respect to the actual displacement of the Paleozoic limestone. The amount of movement is the minimum allowable (based on the data from the McLeod well No. 4), and it is possible that the truncated anticlinal base, from which the Turner Valley fold was dislocated, lies several miles farther west below the thrust sheet.

The period of deformation outlined here is regarded as one continuous, uninterrupted orogenic movement. The folding and faulting began on the west side of the Cordilleran geosyncline and gradually moved toward the east, so that the major faults are folded and re-faulted to a greater extent in the western part than next to the Alberta syncline. The Paleozoic and older rocks underlying the Foothills Belt are probably faulted and folded much the same as in the eastern ranges of the Rocky Mountains, while the Mesozoic rocks of the Foothills Belt are deformed into more complicated and smaller structures. Sediments derived from the growing mountains and deposited on the east are probably represented by the Paskapoo and younger continental deposits found in the Plains of Alberta and Saskatchewan.

The following data have been made available since October 17, 1934 submitting the manuscript to the editor:

The C. & E. Longview well No. 1 in the northwest corner of L.S. 5, Sec. 27, T. 18, R. 2, West of 5th, encountered the major overthrust fault at a depth of 6,215 feet. The Paleozoic limestone was reached at 5,592 feet, and after drilling 623 feet of that formation the drill encountered a fault gouge which appeared to be a mixture of Colorado shale and Belly River sandstone. This places the major fault plane 1,763 feet below sea-level at that location in the extreme south end of the field.

Closed-in pressure tests taken by the Provincial Government during the month of August, 1934, showed a minimum of 445 pounds, a maximum of 1,605 pounds, and a decrease of 0.35 pound per day for the whole field since September 1933. Three new limestone producers have been drilled in since February 1, 1934, and the Provincial Government has set the allowable gas production for the entire field at 252 million cubic feet per day.

SELECTED BIBLIOGRAPHY

1. D. B. Dowling, "Geological Notes to Accompany Map of Sheep River Gas and Oil Field, Alberta," *Geol. Survey of Canada Mem. 52, Geol. Ser. 42* (1914).

2. S. E. Slipper, "Sheep River Gas and Oil Field, Alberta," *Geol. Survey of Canada Mem. 122, Geol. Ser. 104* (1921).

3. F. H. McLearn and G. S. Hume, "The Stratigraphy and Oil Prospects of Alberta, Canada," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 3 (1927), pp. 250–55.

4. G. S. Hume, "Overthrust Faulting and Oil Prospects of the Eastern Foothills of Alberta between the Bow and Highwood Rivers," *Econ. Geol.*, Vol. XXVI, No. 3 (1931), pp. 258–73.

5. ———, "Structure and Oil Prospects of the Eastern Foothills Area, Alberta, between the Highwood and Bow Rivers," *Eng. Inst. of Can. Jour.*, Vol. XIV (January, 1931).

6. ———, "Oil and Gas in Western Canada," *Geol. Survey of Canada, Econ. Geol., Ser. No. 5, Pub. 2128*, 2d Ed. (1933).

7. ———, *Geol. Survey of Canada, Map 257-A, Pub. 2252*, also *Maps 261-A* and *263-A*.

8. G. E. Goodman, "The Structure of Turner Valley Gas Field, Alberta," *Canada Min. & Met. Bull. 224* (December, 1930).

9. Discussion of G. E. Goodman's paper by P. D. Moore, T. A. Link, B. F. Hake, J. B. Webb, Robin Willis, *et al.*, *Canada Min. & Met. Bull. 233* (September, 1931), pp. 1087–1120.

10. Sidney Powers, "Cross-Sections of Turner Valley by P. D. Moore and T. A. Link," *A.I.M.E. Tech. Pub. 377, Pet. Div. 37* (1931), p. 42.

11. P. D. Moore, "Stratigraphy of the Turner Valley Field, Alberta." Manuscript.

12. Theo. A. Link, "The Alberta Syncline, Canada," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 5 (1931).

13. C. S. Evans, "Brisco-Dogtooth Map Area, British Columbia," *Geol. Survey of Canada, Summary Rept., 1932*, Pt. A,2, pp. 106A–76A.

14. J. D. MacKenzie, "The Historical and Structural Geology of the Southernmost Rocky Mountains, *Trans. Roy. Soc. Canada*, Vol. 16, Ser. 3, Sec. 4 (1922).

15. P. D. Moore, "Some Aspects of the Sub-Surface Geology of Alberta," *Stanford University, California Micropaleontology Bull.*, Vol. 3, No. 4 (December, 1932).

DISCUSSION

G. S. HUME, Geological Survey of Canada, Ottawa, Ontario: This paper illustrates the decided relationship between the views regarding origin of certain types of structure and the interpretation. In the present paper Link and Moore present their views on the origin of foothills structures in Alberta in Figure 7. From the series of six diagrams it is obvious that they believe folding first took place and as deformation continued faults occurred along the overturned limbs of the folds. In each case shown on the diagram a fold first develops in front of a fault and these folds in some instances are diagrammatically shown to become recumbent and then faulted. Only in the matter of the degree of overturning and in the stretching along the overturned limb prior to faulting is this conception different from the formation of nappes. Indeed, it would seem that if the faults did result along the overturned limbs of folds, such extreme overturning and stretching would be almost certain to occur. It is a fact, however, that overturned strata in the foothills rarely occur; hence their absence appears to be a strong argument against the conception of the origin of foothills structure as outlined in Figure 7. In one case, diagram E, an anticline is shown to have had its Paleozoic top snipped off by a fault, presumably illustrating the type of structure conceived to be present in Turner Valley. This presumably would be a unique occurrence and the deduction to be drawn from it would be that Turner Valley is a unique structure in the foothills and that other structures of a similar kind may not occur. Many geologists, including the present writer, who have thought other foothills areas offered the same good prospects as Turner Valley but who have been disappointed by drilling results, will sympathize with this view, although they may not yet be wholly convinced. For a totally different conception of the origin of foothills structure, the reader should refer to

Geol. Survey of Canada Summary Report AII, pp. 158–63, by C. S. Evans. Evans conceives of the faults originating at depth, where the "tangential forces of compression are greatest," and developing at an angle of perhaps 35° to 40° until near the surface they break steeply to the surface. As pressure proceeds, following the development of each fault the block above the fault will move upward and forward and ride outward over the surface until

> the compression that started it is balanced or relieved. On the next application of accumulating pressure a new thrust may develop ahead of this one and the block immediately above it will ride forward and up; whereas the block next behind it will be pushed forward and accommodate itself to the movement, not by riding up on the block ahead of it, except to a certain small amount, but by its base sliding forward in the zone of flow, and by movement between it and the block ahead of it on the old fault surface, thus causing a rotation of this older block.

This rotation must cause a steepening of the fault planes back of the fault block in which movement is taking place, the steepening in the case of the foothills where the fault planes dip west being toward the west.

This conception of the origin of foothills structure has several implications quite different from what is thought to be inherent to Link and Moore's conception. In the first place a fault block may be shoved over the surface for considerable distances—much greater than is suggested by Figure 7. It is the writer's contention that the physiographic facts of the foothills show that the present limestone block which now constitutes the mountain front has been formerly much more extensive and may have covered a large part of the foothills. Evidence of this is believed to be presented by the more rugged topography in the western foothills in comparison with the eastern the result being ascribed to a shorter time of erosion subsequent to the retreat of the overlying fault plate; by the superimposed streams and rivers cutting directly across the strike of both formations and structures and by the fact that such overthrust masses as Crowsnest Mountain, now 3 miles in front of the Lewis thrust, point to erosion of the mountain front measured in miles. The structure of the foothills, therefore, according to the writer, should be interpreted in the light of an overlying fault plate during their development. Perhaps the most important deduction to be drawn from this, as stated by Evans, is that each fault block moved forward by movement between it and the overlying block causing a rotation and steepening of the fault planes. It is, therefore, believed that the foothills should show steeper faults subsidiary to the sole faults than is postulated by Link and Moore. In the foothills many of the faults are concealed, but mapping seems to leave little doubt that most of them are straight regardless of topography and the writer has interpreted them as being steeper than 65°. Where faults of this type have been observed at the surface, they are almost invariably steep, even being vertical in a few places. This over-steepening of thrust faults is to be explained, according to the writer's conception, by rotation, as already explained. Thus it would seem that if steep faults, subsidiary to the sole faults, are present elsewhere in the foothills, they would also be expected in Turner Valley. Undoubtedly the medium-angle faults shown by Link and Moore in sections *B–B'*, *C–C'*, *E–E'* on the west flank of Turner Valley explain the repetition of strata as encountered in the wells, but the faults can hardly be as shown. In section *B–B'*, for example, the west fault of Turner Valley must displace the grit bed to an amount somewhat comparable with the amount of displacement shown for the Cardium. If the fault is approximately parallel to the Cardium, as

shown, it is difficult to imagine what has happened to the grit bed on the upthrown side of the fault; in fact the situation as shown in the section seems impossible. As far as the writer can see, the difficulty can only be overcome by steepening the fault to a degree considerably greater than the stratification of the beds immediately overlying it, so that the fault cuts lower stratigraphic horizons downward. This same objection can be raised in regard to the west fault in Turner Valley shown in section *C–C′*, but here the objection does not appear so obvious, since the fault is only shown as displacing one horizon. In section *E–E′*, however, the Home sand and Paleozoic limestone would have to be moved upwards on the upthrown side of the fault to an amount approaching that on the grit bed and the Cardium. The only apparent way to obviate the difficulty of accommodating the thickness of beds involved seems to be to consider the fault steeper than the dip of the strata immediately above it. The writer has difficulty, too, in agreeing with the interpretation of the fault in section *E–E′* that is shown only in the upper strata and diminishing in throw downward, unless the displacement is horizontal along the strike of the fault. In relation to the Paleozoic limestone these strata are non-competent, and it is believed part of a fault movement that might take place in the competent beds would be absorbed by the soft, non-competent beds so that the displacement along the fault should decrease upward.

Evans' conception of the development of the thrust faults allows for the faulting without any considerable preceding folding, and the folding in the foothills has been regarded by the writer as mainly resulting from the faulting. On this conception of faulting, therefore, Turner Valley structure becomes a drag fold developed above the sole fault, the beds on the east flank having a tendency to be underturned due to the drag along the fault. The result as far as the major structure of Turner Valley is concerned is identical with that shown by Link and Moore, but Turner Valley would probably not be unique, as it might well be if their conception of origin is proved to be correct.

In regard to the outcrop of the sole fault east of Turner Valley the writer agrees that its outcrop probably is farther west than is shown on his map (G.S.C. 257A) as Link and Moore believe. It is believed by the writer, however, that the fault east of Turner Valley is only part of a large fault which continues north along the eastern edge of the foothills and structurally separates the foothills from the plains. He regrets that in their paper Link and Moore did not present the evidence for their belief that the Turner Valley sole fault curves westward south of the north branch of Sheep River and ends against the Millarville sole fault on Section 35. As Link and Moore show this fault, it cuts across the Belly River east flank of Turner Valley. In Figure 2 the fault under Turner Valley is conceived to have a displacement of a magnitude ranging from 1 to 1½ miles. Surely such a fault would be expected to make a very pronounced offset in the Belly River east flank ridge. The topography of the ridge suggests no such large offset. The Imperial Oil geologists mapped these ridges in much greater detail than did the Geological Survey and no doubt have data that are unknown to the writer. The same objection might be made to the Millarville sole fault, where, according to Link and Moore, it crosses the Belly River west flank of Turner Valley. The objection here, however, is not so great, because the displacement on the fault is apparently thought to be considerably less than on the Turner Valley sole fault.

In regard to the profile of the faults as shown in Figure 7, it is noticeable that fault 5, diagram F, is somewhat different from the others, particularly 1, 2 and 3. The profile of fault 5 is closely similar to the writer's present conception based on the study of faults during 1933 in the western foothills in the vicinity of Red Deer River. Here there is a low-angle fault, the only one of any magnitude that the writer has been able to map with any certainty. At its outcrop the stratigraphic displacement on the fault is approximately 5,000 feet and the fault plane shows a west dip in places as low as 10°, although generally somewhat higher. The result is that since the foothills in this area have a relief up to 1,000 feet, the fault outcrop follows a very sinuous outline. About 5 miles north of Red Deer River, however, this fault, after taking a bend to the west, straightens out and follows a northwest course in a fairly straight line regardless of topography, indicating that the angle of dip of the fault plane has become steep. This northwest steeply dipping extension of the low-angle more southerly fault has been traced for a number of miles. About 15 miles north of Red Deer River, two areas of Paleozoic rocks crop out in the central part of the foothills. The strata exposed on Red Deer River on the strike of these outcrops are Upper Cretaceous beds 5,000–6,000 feet higher stratigraphically in the section. The deduction drawn from this is that regionally the structure seems higher toward the north and erosion has been considerably deeper. Applying this to the fault already described, it is suggested that the deeper erosion in the north has eroded off the low-angle portion of the fault that occurs in the vicinity of Red Deer River, and revealed a steeper lower part, probably considerably steeper than that shown for fault 5 in Figure 7. Space does not permit a more detailed account of the characters of faults deduced from the study of the foothills, but suffice it to say the writer agrees with Link and Moore that the low-angle parts of these faults, as in fault 5 in Figure 7, pass upward into steeper faults. This upper steeper part and an intermediate flatter part of faults are known in a number of structures within the foothills. The writer believes that the admission of a deeper, steeper part to these faults explains many features which otherwise present extreme difficulties. For example, the total displacement on a sole fault will be large in comparison with the stratigraphic displacement, especially if the angle of the fault approaches the angle of dip of the beds. If the beds on the sole part of the fault are derived from a deeper, steeper part of the same fault, this difficulty is overcome. Thus in Figure 2, if the Turner Valley sole fault turned down steeply somewhere in the vicinity of the west part of the upthrust limestone, the difficulty that the section now presents, namely, the cutting off of the bottom of the syncline west of Turner Valley, would be overcome.

In regard to the contour maps, the writer has no comments because he has not had the opportunity to examine all wells in such detail as Link and Moore obviously have done, although, due to his conception of the formation of foothills structures, it is a surprise to him to find so few faults cutting the more competent beds of the section, the Paleozoic limestones.

In conclusion, the writer wishes to state his appreciation to Link and Moore for allowing him to see the manuscript and sections prior to publication in order that he might contribute to the discussion. Any attempt to explain all the features exhibited by such a complex structure as Turner Valley is commendable and, as will be evident from this discussion, differences of opin-

ion between Link and Moore and the writer are based on theoretical considerations which lead to somewhat different interpretations of facts concerning which both of us agree. The great number of data that have had to be taken into consideration and given their proper value, and the problem of correct correlation of wells due to crooked holes, has made this task of presenting a structural picture of Turner Valley extremely difficult and Link and Moore are to be highly congratulated on the result achieved.

THEODORE A. LINK: The discussion of Mr. Moore's and my contribution on the structure of Turner Valley by Dr. Hume bears out our contention that there are bound to be differences of opinion regarding theoretical points and interpretation of details. I regard Dr. Hume's discussion as an asset to the paper, because of his wide experience in the same area. Dr. Hume's objections will be answered in the same order as they appear in his discussion with the hope that all points will be clarified as much as possible.

I can not agree with Dr. Hume's statement that "overturned strata in the foothills rarely occur." They are extremely common in secondary folds and also present in major structures like Turner Valley. The results obtained at United No. 4, described in the paper under discussion, show clearly that the limestone is overturned on the east side of Turner Valley at that location. The overturning of the Cardium sandstone at Great West No. 1 and British Dominion No. 1, also described in the paper, likewise refute Dr. Hume's statement as far as Turner Valley is concerned. My field notes and maps contain records of many overturned beds throughout the foothills area, and my impression is, that although overturning is not present on all major folds, it is present in many places and, in particular, it has been demonstrated for Turner Valley. It was also found in the limestone on the east flank of the Highwood structure in the Highwood well No. 1 and it occurs in places at Grease Creek and the extreme north end of the Jumping Pound structure. The last two named are structures which closely resemble Turner Valley. There are relatively few structures in the foothills where one can definitely decide that the east and west flanks are in reality complements of one another in a simple anticlinal structure. Most of the thrust fault sheets do not involve simple anticlinal folds, but nearly all that do, show a tendency to overturn. One of the best examples is the north end of the so-called "Little Coulee structure" which, along Little Red Deer River in Sec. 28, T. 28, R. 6, W. of 5th, exhibits Belly River sandstone beds overturned to the west for a distance of ½ mile. There are other examples too numerous to mention.

The quotation from Evans that "tangential forces of compression are greatest and developing at an angle of perhaps 35° to 40° until near the surface they break steeply to the surface" is very similar to one made by me as follows:[23]

> In the opinion of the writer the high-angle thrust faults exposed in the Foothills belt of Alberta, Canada, are deeper-lying low-angle overthrust faults deflected toward the surface by strike tension fissures.

To this one may add that deflection may also be due to encountering a steeply inclined coal seam, lenticular sand bodies, etc. The Turner Valley fault is an example.

[23] Theodore A. Link, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12, No. 8 (August, 1928), p. 844.

I can not subscribe to the view that faulting preceded folding to the extent postulated by Evans and Hume. There is a great preponderance of west-dipping fault blocks in certain areas of the Foothills where essentially no preliminary folding is in evidence, but there are numerous examples of well developed folds, such as Turner Valley, where all the evidence points to preliminary folding. It is these folds which interest the petroleum geologist in particular. There may also be true nappes in the Foothills area.

Secondary features, such as minor adjustment faulting, rotation, undertucking and underthrusting are all put forth in our contribution. As an excellent summary of some of the phenomena observed in the Foothills belt, I cite several excerpts from Cadell's[24] conclusions:

1. Horizontal pressure applied at one point is not propagated far forward into a mass of strata.
3. After a certain amount of heaping up along a series of minor thrust-planes, the heaped-up mass tends to rise and ride forward bodily along major thrust-planes.
5. A thrust-plane below may pass into an anticline above, and never reach the surface.
7. A thrust-plane may branch into smaller thrust-planes, or pass into an over-fold along the strike.
9. The more rigid the rock, the better will the phenomenon of thrusting be exhibited.
10. Fan structure may be produced by the continued compression of a single anticline.

It is natural that I should favor these conclusions because of having performed experiments similar to those of Cadell. However, I believe that the material used and the method of pressure application by Cadell favored primarily faulting much more than folding.

Dr. Hume's contention that "the present limestone block which now constitutes the mountain front has been once more extensive and may have covered a large part of the Foothills," is probable, but can not be demonstrated conclusively. In the Waterton Lakes area this seems to be definitely established. J. D. MacKenzie[25] made this same suggestion in 1922 and wrote,

> The fact that the ridges are higher and steeper in that part of the area adjacent to the mountain front is significant and may indicate that the present foothills region was formerly covered by the overthrust block, which protected the western ridges from erosion for a longer time than it did the eastern ones.

I believe that the physiographic evidence which Dr. Hume utilizes to establish the point is not conclusive. The most subdued Foothills topography in all of Alberta is that portion lying in the Cardston-Waterton Lakes area, directly in front of the great Lewis overthrust fault escarpment, where it is probable that the Lewis overthrust sheet once covered part of the Foothills. Thus the theory falls down on specific application. To this contention one might object with the statement that the Cardston Foothills area is covered with considerably more glacial debris than other parts farther north. This is true, and in my opinion is the explanation for the subdued topography in the eastern portion of the Foothills compared with the more rugged nearest the mountains. Near the mountains the Cordilleran ice tongues were active

[24] H. M. Cadell, "Experimental Researches in Mountain Building," *Trans. Roy. Soc. Edinburgh 35* (1890), pp. 337–57.

[25] J. D. MacKenzie, "The Historical and Structural Geology of the Southernmost Rocky Mountains of Canada," *Trans. Roy. Soc. Canada*, Vol. 16, Ser. 3, Sec. 4 (1922).

agents of erosion, while farther east they deployed and were agents of deposition, thus subduing the topography. I believe that this theory can more readily be demonstrated than Hume's and MacKenzie's "fault-plate" theory.

I am also convinced that the Rocky Mountain front, like the eastern edge of the Foothills, is not bounded by one continuous overthrust fault, but by a series of thrust faults which over- and under-lap at their linear extremities. These thrust sheets or plates are, no doubt, of variable thickness, exhibit varying degrees of dip, and different amounts of displacement. The Highwood uplift is quite different from the Turner Valley overthrust sheet, and south of Turner Valley the Highwood Sheet becomes the outermost Foothills structure.

Dr. Hume's contention "that the Foothills should show steeper faults subsidiary to the sole faults" than we postulated can not be accepted as far as Turner Valley is concerned after working on the structure-contour maps on the four datum planes, and the numerous cross sections. As stated in our paper, we found it necessary to discard the high-angle faults in favor of the lower-angle ones *in the case of Turner Valley.* There is no doubt in my mind that high-angle faults are extremely common in the Foothills, as can be observed in the large cross section, Figure 2. They have always been regarded as such by us, but when they do not fit the facts they must be discarded, as in cross sections *B–B′* and *C–C′*. With respect to section *E–E′*, not enough data are available at the present time to settle the question, but the objection to the fault because it diminishes in throw downwards is not serious. These secondary faults are merely adjustment features and may die out *upward* or *downward*. Experiments bear this out most conclusively.[26]

> On the flanks of a fan fold which may develop because of the adjustment of a less competent bed, caught in the core of a major fold between competent strata or series of beds, adjustment by overthrust and underthrust may develop on either side of the fan fold, *and the upward or downward extension of such fault may necessarily be limited.*

(The italics are mine.) The just cited conclusions also apply to other than fan folds.

The evidence for our belief that the Turner Valley sole fault curves westward underneath the Millarville sole fault, as stated in the paper, is based upon results obtained in Foothills No. 4, and experimental data. It is not conclusive, but appeals to me as very probable. *The observed stratigraphic displacement of the major sole faults is not a criterion as to their magnitude,* and the topography of the compound ridges in that locality is very suggestive of our interpretation. The Millarville sole fault was mapped by me from surface evidence and was established beyond a doubt by shallow-structure core-drilling. This fault is interpreted as a hinge thrust fault with increase of displacement northward.

I have also mapped portions of the low-angle sole fault referred to by Dr. Hume in the Red Deer River area, but it is not the only one which can be recognized as such. There are others which were mapped and interpreted as such before verification by drilling. Two of these are the Outwest and the Fisher Mountain sole faults. Regarding the latter, I committed myself quite definitely in print as follows.[27]

[26] Theodore A. Link, "Individualism of Orogenics as Suggested by Experiments." *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 4 (April, 1931).

[27] T. A. Link, Discussion on "Structure and Oil Prospects in Eastern Foothills Area, Alberta," *Eng. Jour. of Canada*, Vol. 14, No. 6 (1931), p. 344.

He (Link) pointed out that the Fisher Creek structure was underlain by what appeared to be a very low-angle overthrust fault and that the topographic expression of this major fault was such that the Fisher Mountain uplift appeared to be a thin overthrust sheet of considerable areal extent.

Drilling of the Cottonbelt No. 1 verified this conclusion. Another well known thrust sheet of this nature is the Twin Butte sheet in the Pincher Creek Foothills area. Four miles west of its surface trace, the drill passed through the sole fault at the shallow depth of 3,870 feet in Yarrow No. 1. The decrease or increase in angle of dip of such faults along their strike is a thing to be expected, and not to be regarded as startling. I believe that was made clear in our paper, although not specifically mentioned. There is no need of worrying about the "cutting off" of synclines or anticlines by low-angle faults in the Foothills. We have definite data that such has been the case. There is such a syncline on the east edge of the Outwest overthrust sheet in the Belly River sandstone (Fig. 2), and the Red Deer River fault, referred to by Hume, also has a very large Belly River syncline sheared off at the base in the Colorado shale.

Since the data from well logs show no evidence of more secondary faults cutting the Paleozoic limestone, no more were shown on the structure-contour maps and the cross sections. I regard the structure as complicated enough without adding more faults, unless evidence warrants it. The absence of appreciable amounts of sulphur in the sands above the limestone also suggests no pollution from below along faults.

In conclusion, I wish to thank Dr. Hume for his criticisms and complimentary remarks regarding our contribution.

B. F. Hake, Calgary, Alberta: In this paper Link and Moore undoubtedly make an important contribution to the geologic literature of North America, for there are few if any other areas in the continent where such an extremely complex geological situation has been so thoroughly investigated. In Turner Valley Moore spent years of intense effort in developing a detailed geologic column from subsurface data, and Link painstakingly secured all available surface information and has assiduously applied his exceptional knowledge, ability, and imagination, to the interpretation of the data and the solution of the problems involved.

To the writer it seems that where not "hampered by facts," that is, underground in undrilled areas, the authors have granted so much latitude to the imagination as to become somewhat inconsistent. In those portions of the sections controlled by wells and in the constructions of the contour maps the principles of similar folding have been followed very faithfully, and rather uniform stratigraphic thicknesses have been used. It would seem that if the same course had been consistently followed in other parts of the cross sections the surface of the top of the Madison limestone might have been quite differently portrayed.

Where controlled by the logs of wells the strata in these sections generally make fair-sized angles with the fault planes, but in other parts of the sections there is a somewhat startling tendency to parallelism between the fault planes and bedding. In those parts of the sections dealing with the rocks with which we are acquainted from field observation, the fault planes display a general tendency to flatten with depth. Below that, in what might be called the *zone of conjecture*, fault planes are shown as steepening downward. Since the value of these cross sections is dependent upon the validity of the theories

which influenced their construction, it would seem that the apparent employment of different principles in separate parts of the sections requires explanation.

In an area where numerous thrust faults cut a closely folded series of incompetent sediments, the range of possible subsurface constructions which can be made without violating the available precise data is so great as to be almost overwhelming and perhaps disheartening, and thus the geologist is likely to prefer that which most nearly fits his own ideas of structural theory. The present writer wishes to point out that there is applicable to this region at least one structural principle to which the authors of the paper appear to have attached but little importance. That is the fact that when a thick series of stratified rocks is sharply folded a large amount of bedding slippage is demanded and if such can not take place according to the requirements, then folding or crumpling or both *must* take place as compensation for the lack of adjustment by bedding-plane slippage.

The writer[28] has suggested that many of the thrust faults in the Canadian Foothills may be simply substitutes for bedding-plane slippage where the incompetence of the sediments did not permit the latter to be effective. Thrust faults of this type are believed to be developed as a means of displacing material from the interior of folding synclines, and where such synclines are asymmetrical, thrust faults will be most numerous on or perhaps confined to the gentler limbs. Observation has led the writer to believe that during the Rocky Mountain orogeny in Alberta, the Paleozoic limestone series formed large competent folds, whereas the overlying Mesozoic sediments were incompetent. The major anticlines were generally asymmetrical and during the growth of such anticlines the incompetent Mesozoic strata occupying the intervening synclines were subjected to rotational shearing stresses. The Mesozoic sediments, being incompetent to transmit these stresses over long distances or to form large arches, buckled and sheared, thus developing thrust faults making low or moderate angles with the bedding planes of the Mesozoic rocks.

It is conceived that under such conditions thrust faults would develop first by the shearing of the stronger beds within the Mesozoic column and such faults would grow both upward and downward from their origins, so that displacements would be maximum at the points of origin and would decrease both upward and downward therefrom. This condition would be modified where distortion of one or both fault blocks induced extension of the wall or walls of a fault by means of bedding-plane slippage and gliding of the folded ends of strata along the plane.

With respect to most thrust faults in the Foothills of Alberta, the writer considers it unnecessary to assume that they extend downward to the zone of flow or even to a conjunction with some master or sole fault. Branching faults unquestionably occur in this region and many observed faults appear to be subsidiary to some master fault. Where some direct evidence suggests such relationships, the writer takes no exception to such an interpretation, but merely desires to point out that such relationships are not the only tenable explanation for conditions observed in this region.

[28] Unpublished manuscript read before the Can. Inst. of Min. and Met., Annual Western Meeting, Edmonton, Alberta, October 1929; and B. F. Hake, Robin Willis, and C. C. Addison, "Folded Thrust Faults in the Foothills of Alberta," manuscript in the hands of the editor, *Geol. Soc. of America*, May, 1934.

The writer and his associates[29] have studied an area in the Foothills where large thrust faults and the sediments cut by them have unquestionably been intricately folded. It is suggested that such a sequence of events may prove to be the true explanation of many puzzling geological relationships in the Alberta Foothills.

The writer is inclined to agree with Link in a feeling of skepticism concerning the hypothesis expressed in Hume's discussion of this paper that "the structure of the Foothills . . . should be interpreted in the light of an overlying fault plate during their development." Some of the overthrust masses of these Foothills have no doubt been considerably reduced by erosion, but the writer has found no reason to believe that the development of foothill structure in Alberta was preceded and controlled by the development of major faults as postulated by Evans.[30]

LINK: The discussion by Mr. Hake is very interesting and his alternative interpretation of the fault problem appears very plausible. The cross sections, as submitted in the paper, might be altered slightly, but if such were done the entire picture would have to undergo considerable revision which would be difficult to adjust to the data available at the present time.

[29] *Op. cit.*

[30] C. S. Evans, "Brisco-Dogtooth Map-Area, British Columbia," *Geol. Survey of Canada, Summ. Rept. 1932*, Pt. A 11.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 11 (NOVEMBER, 1934), PP. 1454-1492, 8 FIGS

RELATIONSHIP OF GEOLOGY TO UNIT OPERATION OF OIL AND GAS FIELDS, INVOLVING GOVERNMENT LANDS[1]

C. DWIGHT AVERY[2] AND J. CHARLES MILLER[2]
Washington, D. C.

ABSTRACT

An endeavor is made to outline the history of that phase of the conservation movement which has led to unit operation since the World War period; also to show that the geologist has played a vital part in furthering its cause and in bringing the petroleum industry to an appreciation of the advantages of developing an oil and gas structure as a geological unit.

A summary is given of the geology of six oil and gas fields involving public lands in the western United States now under unit operation, namely, North and Middle domes of Kettleman Hills, California, Little Buffalo Basin, Big Sand Draw, Billy Creek, and Pitchfork fields in Wyoming. The geology of the McCallum field, North Park, Colorado, for which unit operation is contemplated, is also reviewed.

The Federal laws and regulations governing unit operation on lands in which mineral title is still in the Government are cited and the salient geological and administrative features to be considered in the presentation of plans for unit operation or coöperative development for approval by the Secretary of the Interior are suggested.

INTRODUCTION

Purpose.—As a means of acquainting geologists and engineers with the administrative procedure under the Federal statutes and the regulations of the Department of the Interior, it is believed to be appropriate to present concrete examples of fields for which plans of unit operation or coöperative development have been approved by the Secretary and to supplement these with an example of a field for which unit operation is contemplated. In the discussion of the agreements covering unit or coöperative development of fields mentioned, it is to be clearly understood that such interpretation of contracts or agreements as is here presented is in no wise to be considered as an official determination by the Department of the Interior; rather the writers intend to convey to geologists the purport of such portions of the agreements as arise from consideration of the geology of the areas involved. This purpose is served by a presentation of available geological information concerning the fields discussed but it is not in-

[1] Read before the Association at the Dallas meeting, March 23, 1934. Manuscript received, March 24, 1934. Published by permission of the director of the United States Geological Survey.

[2] United States Geological Survey.

tended to suggest that any contribution to our knowledge of the geology of those fields is presented. It is hoped, rather, that the examples given will be of assistance to geologists in formulating other unit plans and that they will tend to show progress in the realization of this important advance toward a national policy of oil and gas conservation. In so far as reiteration of well established or much discussed principles is included, the purpose is to give a sufficiently complete statement of the problem to serve as a basis for tracing the history of the movement for unit operation which was initiated by scientists in the Government service during the World-War period and emphasized within the industry by Henry L. Doherty and others. In addition an endeavor is made to demonstrate that the geological map is a primary component and an essential constituent of any unit or coöperative plan of development of an oil and gas field.

Acknowledgments.—The writers are grateful to the geologists whose reports were utilized in the preparation of this paper, including those members or former members of the Geological Survey whose published and unpublished reports include the structure-contour maps and other information on the oil and gas fields discussed. They are also indebted to W. C. Mendenhall, director, United States Geological Survey, to Herman Stabler, chief, and to John D. Northrop, assistant chief, of the Conservation Branch of the United States Geological Survey, for suggestions and coöperation in the preparation of this paper.

HISTORICAL PHASES

Initiation.—The need for conservation of our mineral resources was first most effectively brought to public attention at a meeting of the Governors of the States in Washington in May, 1908, called by President Theodore Roosevelt, although this need had long been recognized by scientists and minor Government officials. Following this meeting the President created the National Conservation Commission on June 8, 1908. This Commission issued a report in February, 1909, dealing with conservation in all its phases. Selected papers written by members of the Geological Survey in response to an Executive order were printed separately in 1909 as *United States Geological Survey Bulletin No. 394* entitled "Papers on the Conservation of Mineral Resources." Two chapters in this bulletin on the petroleum and the natural gas resources of the United States, written by David T. Day, dimly foreshadowed unit operation as a conservation measure when he stated (page 44) that:

It is impossible to prevent the consequent rapid depletion of a field with-

out a combination of all the interests, or by limiting by statute the amount that each producer shall extract per acre within a specified time.

On page 49 of this bulletin under the caption of "How Supplies of Petroleum May be Extended," Day stated that:

> Legislation tending to the capping of gas wells in petroleum fields, to preserve the pressure, and to prevent the unnecessary encroachment of water should be extended to all States where petroleum is produced.

Between 1907 and 1910 and in subsequent years upon recommendation of the Land Classification Board of the Geological Survey of which W. C. Mendenhall, present director of the Geological Survey, was chief, large areas of possible oil land included in the public domain were withdrawn from settlement, location, sale, or entry, and reserved for classification and in the aid of legislation affecting their use and disposition. These withdrawals, the legal basis and purpose of which are fully discussed in *United States Geological Survey Bulletin 623*, by Max W. Ball, published in 1917, were made in order to afford the Government opportunity to examine geologically these areas and to determine the oil or non-oil character of the lands. As a conservation measure these withdrawals were intended to insure the utilization of these lands for their greatest value.

The need of the armed powers during the World War brought about an acute realization of the importance of mineral resources, among them petroleum, as a basis of national security, although these needs had been in a measure foreseen in America when the first Naval Petroleum Reserve was created in 1912.

As early as 1916 Government scientists, notably those in the Bureau of Mines and the Geological Survey, were engaged in investigation and research designed to advise and direct the petroleum industry toward a better economic policy through the application of scientific methods to production technique. In a paper[3] delivered in 1916 before the American Mining Congress, Ball stated in conclusion:

> If you would prevent waste of oil and natural gas, if you would do away with careless drilling methods, excessive production charges and storage losses, if you would insure the production of the maximum amount of oil at the minimum cost, if you would help to maintain a reasonable price for petroleum and its products in the years to come; then do your part in creating public sentiment in favor of adequate acreage. You may not find it popular propaganda just now. You will doubtless be accused of advocating monopoly and probably branded as a corporation partisan. But if you take one step toward imbedding the acreage idea in the popular mind, or incorporating it into State legislation, or embodying it in oil-field practice, you will have assisted in conserving the oil and gas deposits of the United States and will have rendered a valuable public service.

[3] Max W. Ball, "Adequate Acreage and Oil Conservation," *Proc. Am. Mining Congress, 19th Session, Nov. 13–16, 1916*, pp. 322–33.

In suggesting a constructive economic policy, Gilbert and Pogue[4] stated, in 1918, that:

This country has applied the laissez-faire and advisory policies to petroleum without adequate betterment of the situation so far as wastes are concerned. It has even tried certain forms of legislative or dictatorial force in the way of interjecting competition into phases of the matter already integrated or by nature noncompetitive but with no beneficent effect upon the resource as a whole.

With regard to discouragement of unrestricted competition in production these authors stated further that:

The first step toward this end would logically be to disfavor small holdings. In the case of the public lands, this could be accomplished by appropriate legislation permitting the patent or lease of adequate acreage.

In the case of private oil lands either developed or in prospect, a constructive policy will favor and facilitate integration, at least up to the point where each geological unit is occupied by a single producing activity. Anything short of this leads to competitive racing for extraction, the most potent single impetus toward wastefulness. . . . A constructive economic policy may be expected to find means whereby it can protect the public from the undue exercise of the power inherent in large integrated activities. . . . The elimination of excessive competition in oil production, that is to say, of competition within the geological unit or reservoir will go far toward placing petroleum on the same footing with other mineral products.

Wyer[5] also recognized the economic necessity for stabilization methods when he stated that:

The greatest need of the industry today is the adequate recognition of the dominating factors in the natural gas conservation problem, which are:

1. Mandatory pooling of field operations, coupled with an adequate market price;

2. Education of the natural gas producers and of the public coupled with national constructive legislation. Any legislation, of course, to be of value to the public must be so framed as to stimulate production and the constant search for new supplies.

McMurray and Lewis[6] were early in recognizing the need of unit operation in their investigations and in 1916 stated:

The maximum usefulness could be derived from a pool of oil or gas by its being controlled by one competent management as under such conditions it could be developed with the least waste and at the smallest cost. . . . To get the best results the operators should act in unison for the protection of their common sources of supply and for their mutual benefit.

[4] C. G. Gilbert and J. E. Pogue, "Petroleum: A Resource Interpretation," *U. S. National Museum Bulletin 102*, Pt. 6 (1918), pp. 61–65.

[5] S. S. Wyer, "Natural Gas: Its Production, Service, and Conservation," *U. S. Nat. Museum Bull. 102*, Pt. 7 (1918), pp. 62–63.

[6] W. F. McMurray and J. O. Lewis, "Underground Waste in Oil and Gas Fields and Methods of Prevention," *U. S. Bureau of Mines Technical Paper 130* (1916), p. 4.

Within the petroleum industry the conservation movement was emphasized through the efforts of Henry L. Doherty. In a paper delivered at the Fourth Annual Meeting of the American Petroleum Institute at St. Louis, in December, 1923, speaking on "The Utilization of Petroleum Products," Doherty stated:

> The program I have been recommending for some time is this: That we make such changes in the basic methods of producing crude oil that the raw product will be located in vast quantities and blocked out in large amounts so as to be readily accessible and under conditions whereby it will not have to be forced upon the market in excess of what the market can absorb.

In an address before the National Marketers Association at Cleveland, Ohio, November 19, 1924, Doherty[7] outlined his plan for the production of oil in five propositions offered in lieu of then existing methods of developing oil fields. The second of these was "that nobody would be given a permit to drill until an exploration district had been established."

Speaking of the energy value of gas wasted, Doherty[8] stated:

> Gas in some cases to an energy value of more than the entire energy value of all of the oil that is recovered, is blown to the air, and this in spite of the fact that if the gas were conserved it would greatly increase the amount of oil recovered, and would enable every barrel of oil to be raised to the surface without the cost of pumping. . . . . No matter what other checks or restrictions other people may think must be placed on production of oil, it is my belief that we must provide for unit operation of pools. Instead of paying the landowner his royalties according to the amount of oil captured on his land, we must pay all the owners according to the amount of oil that underlay their land as the oil and gas existed as an undisturbed pool. . . .
>
> If unit operation is adopted we can recover at least double as much oil as we do now and can conserve at least 66⅔ per cent of our gas.

In addition, Doherty urged conservation of gas as the most important factor in oil production and urged Federal legislation on conservation measures to insure uniformity throughout the country.

In response to letters by the Federal Oil Conservation Board addressed to leaders in the oil industry during 1925, Henry L. Doherty, John Hays Hammond, Earl Oliver, and others advocated or endorsed the principles of unit operation or coöperative development of oil fields. In its first report[9] presenting certain facts contributed by the

[7] In *National Petroleum News*, Vol. 16, No. 48 (November 26, 1924), Doherty urges Government regulation of drilling and producing of oil, pp. 48–51.

[8] H. L. Doherty, "Suggestions for Conservation of Petroleum by Control of Production," New York Meeting, February, 1925, Am. Inst. Min. Eng., *Production of Petroleum in 1924*, pp. 7–27.

[9] *Report of the Federal Oil Conservation Board to the President of the United States*, Pt. 1 (September, 1926), p. 13.

industry and by Government scientists through the Technical and Advisory Committee of which George Otis Smith, former director of the United States Geological Survey, was chairman, and H. H. Hill, former chief petroleum engineer of the Bureau of Mines, was a member, the Board stated:

Of the fundamental conservation measures (*above-mentioned*), that of coöperative methods in development of new fields to prevent temporary glut merits more exhaustive discussion, as it is a promising field for important action by both industry and the Government.

Under date of January 28, 1928, the committee of nine appointed by the Board, consisting of Henry M. Bates, Jas. A. Veasey, J. Edgar Pew, Abram F. Myers, Walter F. Brown, Thos. A. O'Donnell, E. C. Finney, W. S. Farish, and Warren Olney, Jr., representing the Federal Government, the petroleum industry, and the mineral-law section of the American Bar Association, submitted its report. This committee confined its recommendations to Federal legislation although it urged similar legislation by the oil-producing States. The legislation recommended provided for relief of oil operators from the provisions of the Federal anti-trust acts with proper safeguards in the public interest.

Under date of December 2, 1927, the technical sub-committee of the American Petroleum Institute submitted a report on "The Conservation of Gas" at a meeting in Chicago, Illinois, and this report, urging unit operation as a means of proper utilization of energy of the gas, was transmitted to the board by the committee of nine. Included in the board's third report is also a report of the committee on conservation of mineral resources of the section of mineral law of the American Bar Association suggesting types of uniform State legislation one of which

would legalize voluntary agreements for economic purposes and conservation by removing the obstacles imposed by State antitrust laws, the other measure would provide for compulsory unit and coöperative development and operation by invoking the police power of the State.

Following the trend of the oil-conservation movement, Congress in 1930 enacted temporary legislation providing for participation in unit operation or coöperative development among lessees of public lands in the act approved July 3, 1930 (46 Stat. 1007). This act permitted operators, until January 31, 1931, to make application for approval of unit-operation plans. Under this act plans for unit operation of two fields were approved.

The necessity for additional legislation had been demonstrated and Congress, on March 4, 1931 (46 Stat. 1523), amended sections 17

and 27 of the general leasing act of February 25, 1920 (41 Stat. 437). Provisions were made for approval by the Secretary of the Interior of

> any coöperative or unit plan of development or operation of a single oil or gas pool, or area which includes lands owned by the United States [and for approval of] operating, drilling, or development contracts whenever in his discretion and regardless of acreage limitations provided for in this act, the conservation of natural products or the public convenience or necessity may require it or the interests of the United States may be best subserved thereby.

The changing concepts in methods of petroleum production were given further impetus by the adoption of the "Code of Fair Competition for the Petroleum Industry," signed by the President on August 19, 1933, and modified on September 13, 1933. During the latter part of 1933, the Geological Survey was called upon to pass on the geological phases of applications for approval of twenty or more plans for the orderly development of new pools. Under the regulations approved by the Secretary of the Interior as administrator of the code on December 20, 1933, a new pool is defined as

> any commercially productive accumulation of crude petroleum (whether located in a field, area, or horizon heretofore known as productive or otherwise) discovered after January 1, 1933, and/or in which ten commercially producing wells had not been completed by September 13, 1933.

Secretary Ickes explained that:

> No plan will be approved by me which does not adequately protect the correlative rights of all parties having an interest in the pool, nor will I approve any plan that does not permit full conservation of petroleum resources to prevent the waste of this irreplaceable fuel.
>
> Production from newly discovered fields or pools will be restricted so as not to interfere unduly with existing interstate market for petroleum and its products and drilling in new pools will be curbed to prevent unrestricted development of excessive potentials.

Further evidence of changing sentiment within the industry is shown by the following quotation from a recent statement[10] by the president of the American Petroleum Institute, Axtell J. Byles:

> The public, as well as the oil industry, understands that overproduction of crude oil is responsible for most of its difficulties and the economic waste and evil practices which have followed. It may not be as well understood, however, that the industry up to this time has been unable to achieve a balance of supply with consumer demand by reason of a combination of the law of capture, the laws against restraint of trade, and of small minorities within the industry which—either by reason of avarice or financial exigency, or both—have refused to coöperate in any constructive program. . . .

[10] A. J. Byles, *American Petroleum Institute Quarterly*, Vol. 4, No. 1 (January, 1934), pp. 1 and 2.

No plan of stabilization can be effected unless it is recognized that every pool and operation in each section of the country has a responsibility to every other section and operation. . . . By reason of the fugitive nature of crude oil in place, and the fact that without restraint by Government or enforceable agreement the drilling of a discovery well usually leads to the immediate complete development and early exhaustion of a pool, I would hazard the opinion that in this industry Federal regulation of crude oil production may be necessary for some time to come. Such a policy need not, and should not, involve governmental operation of the industry.

The Unitization Committee of the American Institute of Mining Engineers appointed in October, 1929, of which Earl Oliver was chairman, classified oil and gas pools under four headings: (1) unit pool; (2) near-unit pool; (3) coöperative pool; and (4) competitive pool. They cited as an example of each, in the order enumerated: (1) the "Temple of Solomon" pool in Persia; (2) the Salt Creek pool, Wyoming; (3) the Yates pool, Pecos County, Texas; and finally (4) most pools in the United States. Federal laws and regulations concerning public lands now recognize in effect only two of these, the unit pool and the coöperative pool. Thus with Federal recognition and industrial acceptance, this new concept of oil field development takes its place as an integral part of our national economy.

Justification.—The trend of thought within the oil industry during the past 3 or 4 years has been definitely toward unit operation or coöperative development of fields. This has necessitated a revision of the methods of oil production arising from that basic legal error—the doctrine of capture. Pursuant to a resolution adopted by the board of directors of the American Petroleum Institute, November 19, 1931, the committee on production practice was directed

to prepare and recommend to the board a comprehensive program designed to put in practical operation a principle of oil production, commonly referred to as "the new conception of oil production."

This committee interpreted the resolution of the board as an endorsement of principles which may be stated briefly as follows.

(1) Each owner of the surface is entitled to receive only his equitable and rateable share of the recoverable oil and gas in the pool beneath that owner's land at the time of discovery;

(2) An oil field or pool should be so developed and operated as to recover the maximum quantity of oil therefrom.

The first principle emphasizes the importance of geology in defining the area to be segregated as a unit, the second, the necessity for proper engineering development. As Lahee[11] has pointed out, how-

[11] F. H. Lahee, "Importance of Geology in New Conception of Unit Pool Development," *Oil and Gas Jour.*, Vol. 31, No. 2 (June 2, 1932), pp. 38–39.

ever, "an oil pool is wholly and strictly a geological phenomenon." Accordingly, to the geologist falls the important task of deciding the acreage to be included in a unit either in advance of or subsequent to development. Thereafter the production engineer, the economist, and the administrative officer are important and indispensable participants in the successful consummation of a unit plan of operation.

The justification for unit operation of oil or gas fields is principally economic, exploration costs being lessened by restricted drilling, production expense diminished, reservoir energy conserved, oil and gas reserves retained in the ground until needed, ultimate recovery increased, and the life of the field extended. If generally adopted, unit or coöperative operation would be of vital assistance in controlling production and would tend to balance supply with demand.

PLANS APPROVED BY SECRETARY OF INTERIOR

Since the passage of the acts of July 3, 1930 (46 Stat. 1007), and March 4, 1931 (46 Stat. 1523), unit plans of operation have been approved by the Secretary of the Interior as shown in Table I, their locations being indicated in Figure 1.

The ensuing discussion of the fields listed presents no new or divergent geological data but summarizes the information on which final determination of the areas to be included in the respective unit plans was based.

TABLE I

UNIT OPERATION PLANS INVOLVING GOVERNMENT LANDS

(See Figure 1 for location)

State and Field	*Participating Acreage*	*Total Acreage*	*Date of Approval by Secretary*
CALIFORNIA			
North dome, Kettleman Hills	8,820*	21,200†	Jan. 31, 1931
Middle dome, Kettleman Hills	1,170	15,020	Sept. 30, 1933
South dome, Kettleman Hills	‡	15,000	July 19, 1933§
WYOMING			
Little Buffalo Basin	4,806	4,806	Jan. 6, 1931
Big Sand Draw	1,960	1,960	Feb. 11, 1932
Billy Creek	710	710	April 11, 1932
Pitchfork	570	2,564	Nov. 30, 1932

* Includes only association's holdings as of January 31, 1933, within "brown" line. Acreage between "brown" and "blue" lines held by members subject to modified participation. All lands within "brown" line—17,610 acres. NOTE: Colored lines here mentioned are indicated on maps by words, not colors.

† Includes fee land and association's leaseholds within "blue" line.

‡ Preliminary plan. Participating area not decided. Total area approximate.

§ Date of final approval. Approved as to majority of permits August 4, 1932.

FIG. 1.—Index map, showing approximate locations of oil and gas fields. Outline of fields not to scale. See Table I.

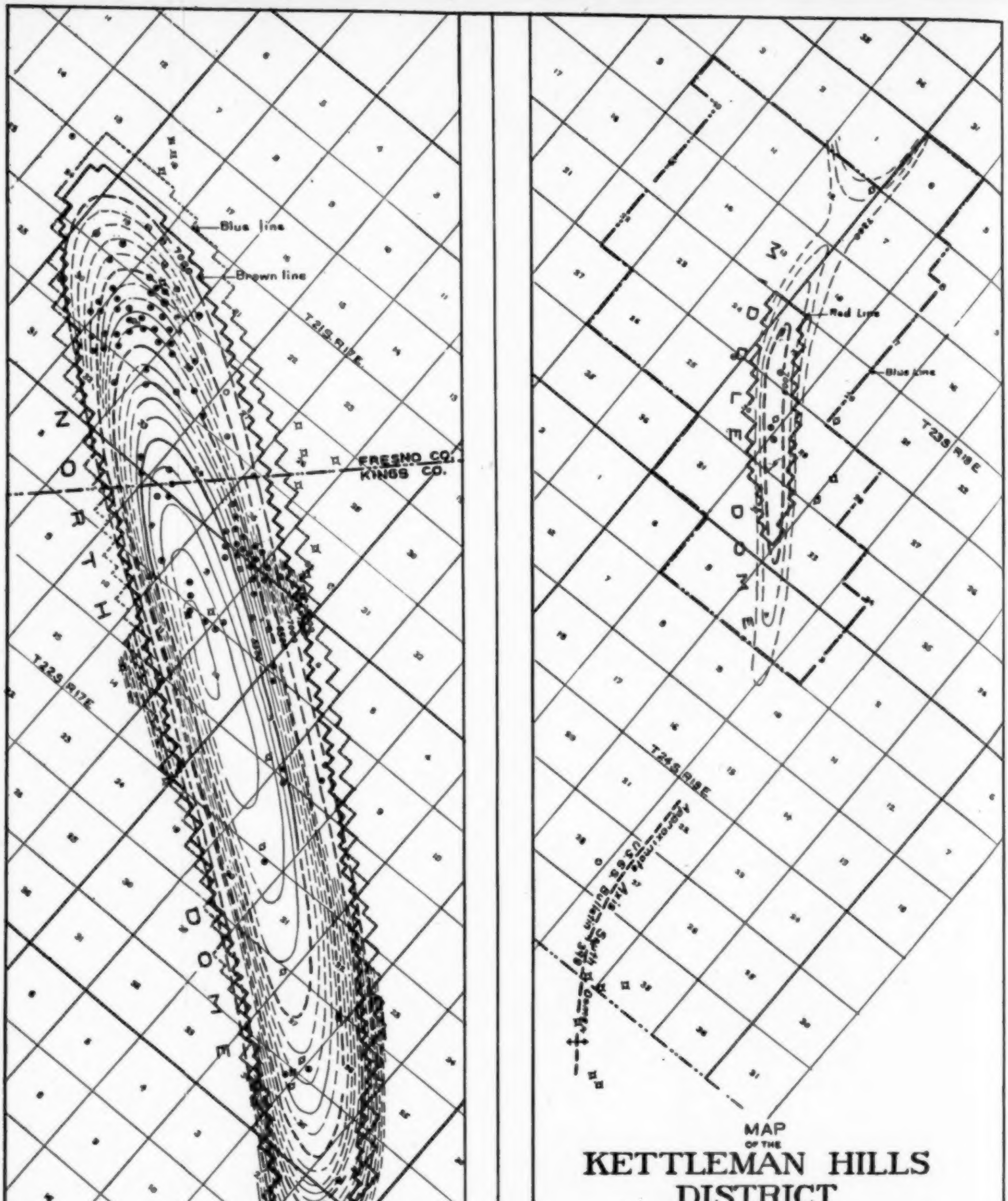


FIG. 2.—Structure-contour map of Kettleman Hills district.

KETTLEMAN HILLS, CALIFORNIA

The Kettleman Hills (Fig. 2) lie chiefly in Kings County, California, extending northward into Fresno County, and southward into Kern County. They occupy an area about 5 miles wide and 30 miles long, extending from northwest to southeast on the west side of San Joaquin Valley between the towns of Coalinga and Lost Hills.

Stratigraphy.—The nomenclature here used is that of Arnold and Anderson[12] and the committee on geologic names[13] although recent work by Gester and Galloway[14] in this field indicates that the classification and age designation of the formations are in need of revision. The marine and nonmarine beds exposed along the crest of the anticlines, consisting of siltstone, clay, and sandstone, were referred by Arnold and Anderson to the Etchegoin formation of Pliocene age. The Etchegoin beds dip under the fresh-water Tulare formation (Pliocene and Pleistocene?).

Most of the wells drilled start in the Etchegoin beds, pass through the Pliocene Jacalitos formation, and at a depth of about 5,000 feet penetrate the Miocene siliceous or "brown" shale (Santa Margarita(?) of Arnold and Anderson) before entering the productive sands of the Temblor (Vaqueros of Arnold and Anderson) at depths between 6,000 and 7,000 feet. The Temblor section has been divided by Gester and Galloway[15] into three lithologic units and they state that the section thickens at the outcrop from Coalinga southward along the Temblor Range and eastward beneath Kettleman Hills. A thickness of 800–1,000 feet has been measured along the east flanks of the Diablo Range west of the Hills and of 1,200–1,600 feet in well logs. A few wells have been drilled through the Temblor (middle Miocene) into the underlying Kreyenhagen shale (Oligocene? and Eocene), and the Eocene sandstone (Tejon of Arnold and Anderson). The deepest well in the district at present is Lillis-Welch No. 1, drilled by the Kettleman Oil and Gas Company on patented land in the NW. $\frac{1}{4}$ of NW. $\frac{1}{4}$, Sec. 24, T. 21 S., R. 16 E. It was drilled to a total depth of 10,944 feet, but a fishing job is now in progress at a depth of 9,703 feet (February, 1934). This well starts in the Tulare formation and probably penetrates the Eocene sands. Although it is seemingly low on the north plunge of the North dome, several oil-bearing sands have been reported.

[12] Ralph Arnold and Robert Anderson, "Geology and Oil Resources of the Coalinga District, California," *U. S. Geol. Survey Bull. 398* (1910).

[13] *Geologic Formation Names That Have Been Used in California from San Francisco Region Southward, Chart 3,* compiled by M. Grace Wilmarth, U. S. Geological Survey (January, 1927).

[14] G. C. Gester and John Galloway, "Geology of Kettleman Hills Oil Field," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 10 (Oct. 1933), pp. 1168–86.

[15] G. C. Gester and John Galloway, *op. cit.*, pp. 1180–81.

Structure.—The Kettleman Hills anticline is divided into three structural units known as the North dome, Middle dome, and South dome, extending *en échelon* northwest and southeast, the axis of each being successively offset toward the west. The accompanying structure-contour map (Fig. 2) showing the minus sea-level elevation of the top of the Temblor sandstone, is reproduced from a map by H. V. Dodd, deputy supervisor, Division of Oil and Gas, Department of Natural Resources, State of California, published in Vol. 17, No. 1, Summary of Operations, July, August, September, 1931. As only one well has been drilled to the Temblor formation on the South dome no contours based on well logs are shown for this structure. Furthermore, whether or not the South dome is a closed structure, separate and distinct from the Lost Hills structure, is as yet unknown, owing to a cover of alluvium which obscures all but the north end, and to the lack of sufficient subsurface information from well logs.

Productive sands.—The Temblor sandstone, representing a thickness of 1,200–1,600 feet, has been tentatively divided into five producing horizons separated by shale, the first three of which contain light oil and gas. The oil in the second and third sand is probably dark toward the flanks of the structure. The fourth and fifth sands produce black oil of about 35° to 37° A.P.I. gravity with minor amounts of gas. The light straw-colored oil varies in gravity between 58° and 61.5° A.P.I. Initial daily production per well ranging from 400 to 30,000 barrels of oil and from 4 million to 175 million cubic feet of gas, has been reported. Casing pressures as high as 2,400 pounds per square inch have been measured in wells on the North dome.

The first producing oil and gas well on North dome was the Elliot well No. 1, of the Milham Exploration Company, completed for production on November 5, 1928, in the SE. $\frac{1}{4}$ of SE. $\frac{1}{4}$, Sec. 2, T. 22 S., R. 17 E., which encountered the Temblor sand at about 6,238 feet and attained a total depth of 7,108 feet. The discovery of oil and gas on the Middle dome was made by the Petroleum Securities Company in its Burbank well No. 1, on the SE. $\frac{1}{4}$ of Sec. 30, T. 23 S., R. 19 E., in which the top of the Temblor was reported at 7,559 feet, and the bottom of the hole at a depth of 9,332 feet.

North dome structure.—The North dome is an elongate dome broken along its flat crest at the surface by several strike faults of considerable length and throw that are combined with an intricate system of minor dip faults with throws varying between 5 feet and 100 feet. The faults are of the normal type. The complicated faulting has produced a graben along the crest of the dome. Available information indicates that the major faults may not extend to the producing

sand, and the structure contour map (Fig. 2) is considered, for the purpose of illustration, a reliable representation of the structure based on information available at the time of its preparation. A closure of about 2,000 feet on the top of the Temblor is shown, which is largely within the "blue line," the outer boundary of what is designated as participating acreage.

Origin of unit plan.—A meeting of company officials was held in Los Angeles on November 13, 1928, to determine a well-spacing program satisfactory to the interested parties. In December, 1928, the Standard Oil Company of California, Marland Oil Company, General Petroleum Company, and Kettleman Oil Corporation agreed to a system of staggered well locations 1,320 feet apart and 660 feet between rows. Acting on the suggestion of George Otis Smith, then director of the United States Geological Survey, the Secretary of the Interior, Ray Lyman Wilbur, on April 8, 1929, approved an order requesting all operators on Government lands in Kettleman Hills and inviting operators on private lands and other parties in interest to confer on a rational and equitable plan of deferred development in order to expedite coöperative action necessary to effect conservation measures, consisting of a suspension of all drilling operations, restriction of production, and agreement as to offsets. Director Smith, as representative of the Secretary, succeeded in bringing the interested parties into an agreement effective July 25, 1929, involving 9 oil and gas prospecting permits and one lease on Government lands issued under the act of February 25, 1920. This action led eventually to the formation of the Kettleman North Dome Association, a non-profit coöperative corporation, and to the agreement for "the unified development and production of oil, gas, and other hydrocarbons," which was approved on January 31, 1931, by the Secretary, pursuant to the act of July 3, 1930. Several independent operators on fee lands totaling 940 acres did not join in the agreement and their failure to coöperate led to the more intensive development noticeable on the map at the north and northeast side of the structure. The Standard Oil Company of California proposed in 1930 that, after consummation of a unit agreement as to other lands, a contract be entered into between the parties thereto and the Standard Oil Company as to harmonious operation of the unit area and Standard fee lands, aggregating nearly half the productive area of the structure. No such contract has been executed but the intermingled lands under control of the Kettleman North Dome Association and the Standard Oil Company have been operated under generally similar policies. In this field we have therefore a unit plan of operation for Government and some private lands, a coöperative

policy affecting the unit area and the principal fee holder, and competitive operation between unit and coöperative participants and a few holders of fee lands in two restricted areas.

Lands involved.—In the determination of the area to be included in the unit operation of the North dome, recourse was had to company maps and publications of the United States Geological Survey. The outline of the North and Middle domes was easily determined from the surface outcrop as shown by airplane photographs, but, owing to the large area to be mapped, some time was required after the discovery of gas and light oil was made before reliable structure contour maps were available. Arnold and Anderson[16] had previously outlined the "limits of possible productive territory" for the greater part of the Hills.

The so-called "red line," not shown on the contour map (Fig. 2), approximates the 6,500-foot contour on the top of the Temblor formation and bounds the minimum participating area. The "blue line," shown on the map by the light dashes, is intended ultimately to approximate the limits of productivity and at all times to define the maximum area of participating acreage. For the first 5 years after the effective date of the agreement the "blue line" may not be contracted but is subject to expansion at any time. At the end of the fifth year and at the end of each subsequent year until the end of the tenth year after the effective date of the agreement, but not thereafter, the "blue line" may be contracted to exclude nonproductive acreage.

The voting power and property rights and interests of the various members of the association are unequal. The interest of each member in the property of the corporation and in the hydrocarbons produced is in the ratio that the member's property within the productive limits of the field bears to the total acreage. Each member is entitled to one vote for each acre of participating land. By participating land as defined in the contract is meant all acreage held by members within the "blue line" (light dashes) amounting to 10,800 acres at present. Participation in the cost of development and operation is borne pro rata (subject to certain specified modification as to lands determined to be nonproductive) by each member holding acreage within the "blue line." The "brown line" shown by the solid line defines a redetermination of the productive acreage as of January 31, 1931, to conform with information supplied by drilling. Acreage between the blue and brown lines is subject to a modified participation. The agreement is in effect as long as oil or gas is produced or drilling operations are conducted.

[16] Ralph Arnold and Robert Anderson, *op. cit.*, *Bull. 398*, Pl. 1.

The acreage within these lines as of January 31, 1933, was as follows.

	Total Acreage Within Blue Line	*Acreage Within Brown Line*	*Acreage Within Red Line*
Kettleman North Dome Association (unit area)	10,800	8,820	6,160*
Standard Oil Co. (coöperative)	9,460	8,160	6,440
Others (competitive)	940	630	480
Total field	21,200	17,610	13,080

* Minimum participating acreage.

There were 50 producing wells on the North dome, 17 wells shut in and 22 drilling wells as of January 31, 1934. The average gas-oil ratio was approximately 7,344 cubic feet per barrel and the average gasoline content was about 1.29 gallons per 1,000 cubic feet of gas. The field has a curtailed production of about 50,000 barrels per day at present.

Middle dome structure.—The Middle dome is smaller than the North dome, being about 8 miles long and 5 miles wide, and the structure is more difficult to determine by reason of the soft friable beds exposed. In general the folding is similar to that of the North dome in producing a rather broad flat and much faulted crest at the surface. Figure 2 shows 300 feet of closure on the top of the Temblor.

Origin of unit plan.—Recognizing the advantage of an agreement in advance of discovery, George Otis Smith urged the formulation of a plan similar to that later consummated by him on July 25, 1929, on the North dome. On May 15, 1929, Secretary Wilbur authorized Director Smith to treat the Middle and South domes separately in bringing the interested parties to agreement. On May 27, 1929, an agreement was entered into providing for suspension of drilling activities on Government lands in the Middle dome until January 1, 1931, under certain conditions, the Secretary agreeing to extend the permits involved for a period of two years.

On April 1, 1931, the Secretary authorized George W. Holland, senior attorney in the Geological Survey, to confer with holders and operators of Government oil and gas prospecting permits and others and to endeavor to renew both the Middle and South dome agreements with a view to consummating coöperative or unit plans authorized under the act of March 4, 1931. These efforts eventually led to the Middle dome agreement which was approved by the Secretary, September 30, 1933, affecting about 15,020 acres. All lands, of whatsoever ownership, are subject to the agreement, approximately 6,460

acres included in 5 prospecting permits being lands of the United States. Pursuant to this agreement a corporation was formed to provide for unified development and operation of the area; to provide for a fair apportionment between the members of any oil, gas, or other hydrocarbons produced; and to provide for the payment by each member of its just and equitable proportion of the cost of development of the area in part as a unit and in part as a modified form of coöperative development with respect to acreage between the "red" and the "blue" lines.

Lands involved.—According to the agreement, the so-called "red" line, the solid line on the map, approximating the 7,000-foot contour on top of the Temblor, may be re-located during the first 5 years of the agreement but may not be contracted after that time has elapsed. Any parcel of land included within the red line after the effective date of the agreement, however, may be considered as within that line for an additional 2 years by vote of the directors even though later developments tend to exclude such land. It then becomes the irreducible limit of participating acreage. The board of directors determines once each year what portion, if any, of the participating acreage was on the effective date of the agreement commercially unproductive. The so-called "blue line," the dash-dot line on the map, bounds the area covered by the agreement which may be included within the red line at any time. That part of the total area between the red and the blue lines is designated nonparticipating acreage and does not participate in contribution to calls for money and in distribution of hydrocarbons. Any member holding nonparticipating acreage may at any time drill a well as its own expense and if a portion of this nonparticipating acreage is determined commercially productive by such drilling, that acreage may be included as participating acreage. Upon such inclusion the association or corporation pays the member the actual cost of drilling plus 50 per cent thereof. Of the 1,170 acres within the "red line," 590 acres are Government land, which is classified as participating acreage. The agreement is in effect as long as the lands covered by the agreement are capable of producing oil or gas in paying quantities.

South dome structure.—The torsional stresses which produced the échelon folds known as the North and Middle domes are reflected in the remnant of a third structure locally known as the South dome. Definite evidence of the existence of a closed structure is considered by some geologists to be lacking and this has given rise to expressions of opinion that the so-called South dome is merely the northward extension of the Lost Hills anticline. An area roughly 4 miles long and 3

miles wide includes most of the marine beds exposed, the south or southeast limit of this area being the alluvium cover. A subsurface structure-contour map of this area is not available.

The only well which was reported to have reached the Temblor on South dome was drilled by the Ohio Oil Company, Smith No. 1, on the SW. $\frac{1}{4}$ of SW. $\frac{1}{4}$, Sec. 35, T. 24 S., R. 19 E. This well was drilled to a total depth of 8,054 feet in March, 1930. The top of the Temblor was encountered at a reported depth of 6,872 feet. This test is not considered by some as conclusive evidence that the structure will be nonproductive.

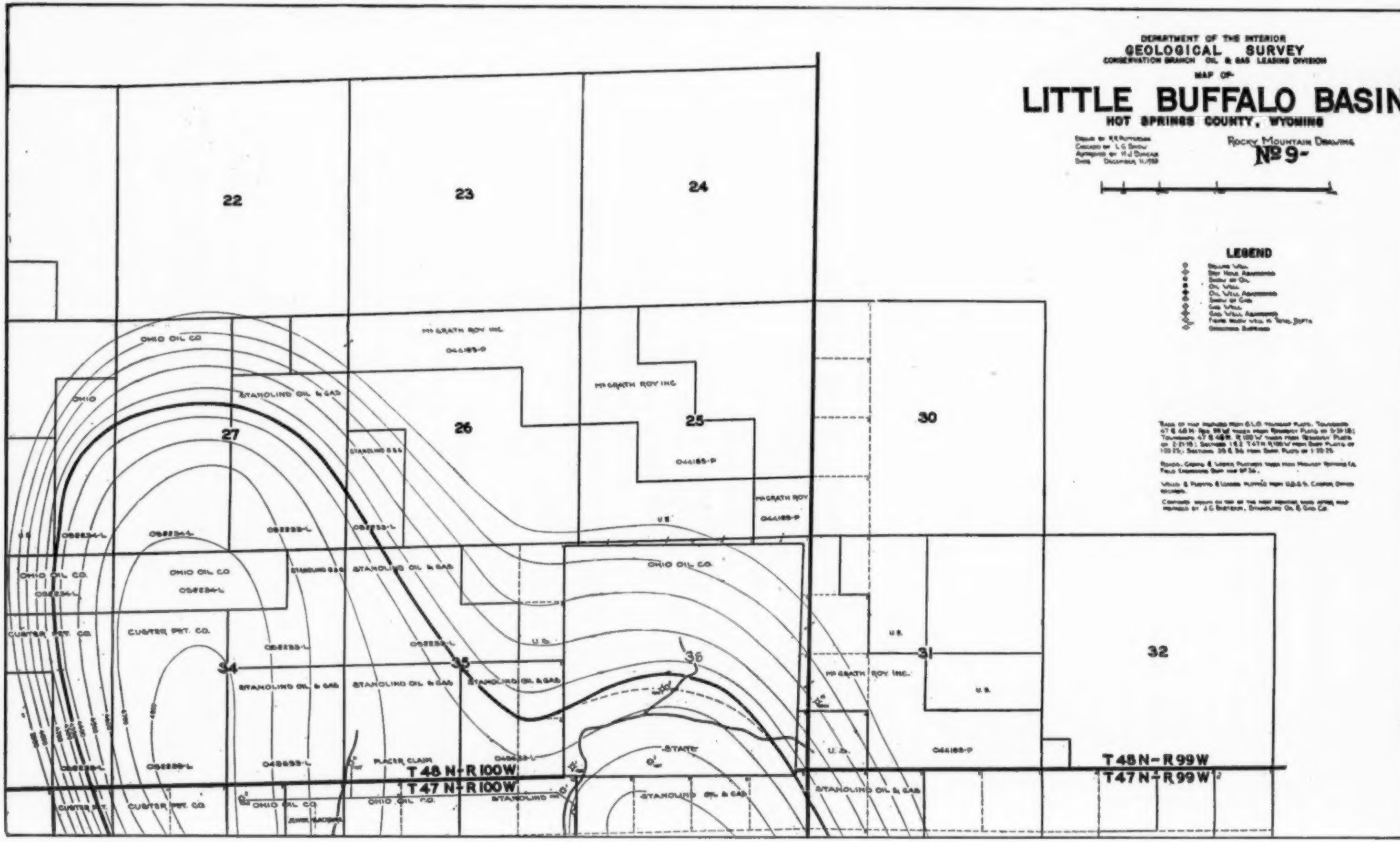
Origin of unit plan.—The negotiations relative to the North and Middle domes led to similar considerations of the South dome area and on July 13, 1929, the holders and operators of Government permits entered into an agreement to suspend all drilling activities under certain conditions until January 1, 1931, with the exception of the Ohio Oil Company's well which was then drilling on Government land. The Secretary of the Interior agreed to extend the permits in the South Dome area for a period of two years. On May 23, 1932, the Secretary again authorized George W. Holland, of the Geological Survey, who subsequently represented the Department in all negotiations looking to the unit plans discussed herein, to confer with the parties in interest for the purpose of formulating a temporary agreement which would ripen into a unitization plan. The task of bringing these parties into agreement was eventually accomplished with the exception of holders of three permits and on August 4, 1932, a second temporary agreement was approved providing for submission of a unit plan within two years and extending the permits to September 23, 1935. On July 19, 1933, Secretary Ickes approved this agreement in so far as it concerned these three permittees or their operators who failed to sign at the earlier date.

Lands involved.—This agreement as approved by the Secretaries on August 4, 1932, and July 19, 1933, is preliminary to the consummation of a unit operation agreement between the holders of 20 oil and gas prospecting permits in the area, involving about 15,000 acres. The unit or coöperative plan is to be submitted within two years after September 23, 1933.

LITTLE BUFFALO BASIN, WYOMING

Stratigraphy.—According to Hewett[17] the lowest beds exposed on the East and West Buffalo anticlines, Wyoming, comprising what is

[17] D. F. Hewett, "Geology and Oil and Coal Resources of the Oregon Basin, Meteetse, and Grass Creek Basin Quadrangles, Wyoming," *U. S. Geol. Survey Prof. Paper 145* (1926), pp. 73–75.



DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
CONSERVATION BRANCH OIL & GAS LEASING DIVISION
MAP OF
LITTLE BUFFALO BASIN
HOT SPRINGS COUNTY, WYOMING
ROCKY MOUNTAIN DRAWING
№ 9
LEGEND
22
23
24
25
26
27
30
31
32
34
35
36
OHIO OIL CO
OHIO OIL CO.
OHIO
McGRATH ROY INC.
STANOLIND OIL & GAS
CUSTER PET. CO.
U.S.
STATE
PLACER CLAIM
T48 N-R100W
T47 N-R100W
T48N-R99W
T47N-R99W

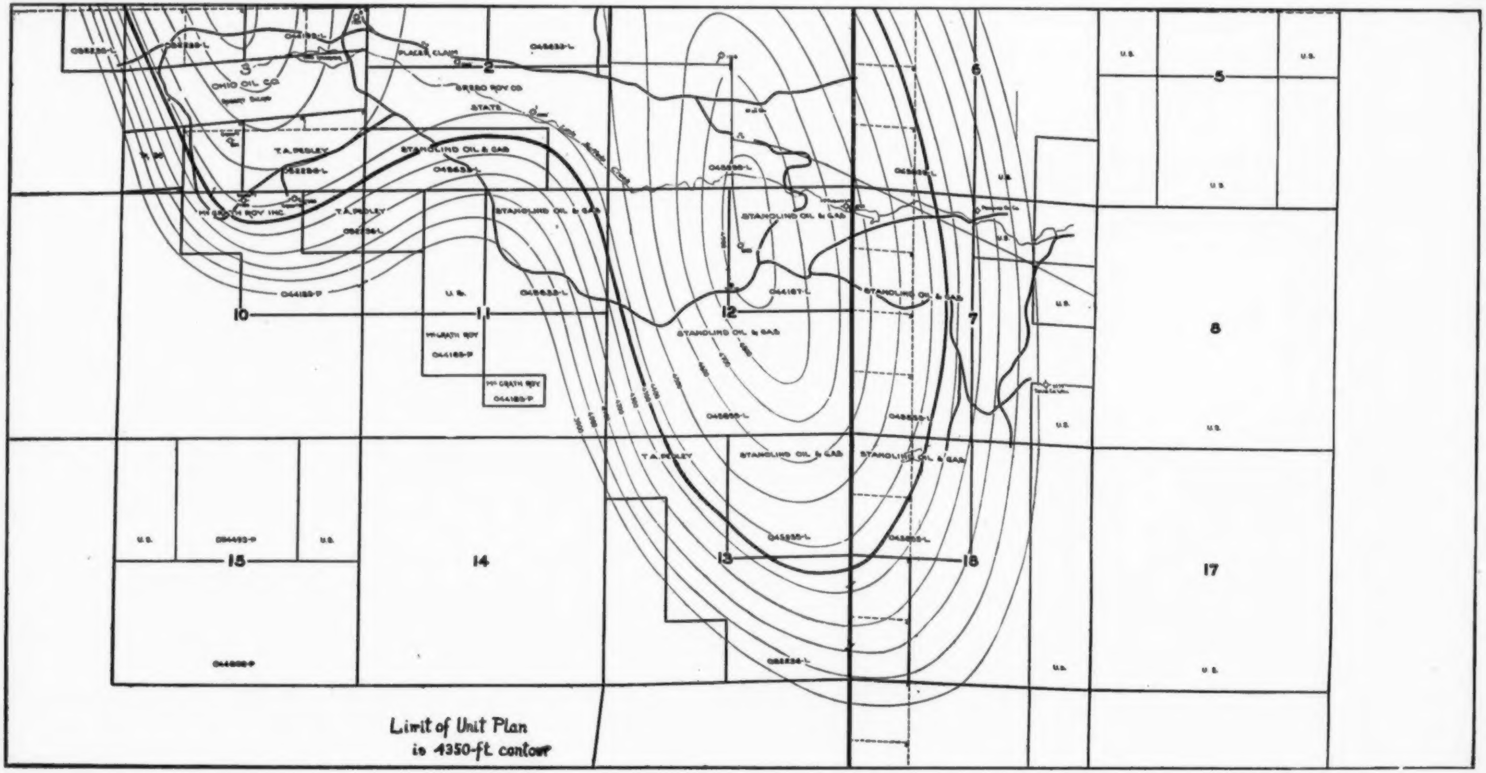


FIG. 3.—Structure-contour map of Little Buffalo Basin field.

known as the Little Buffalo Basin field (Fig. 3), are in the upper 1,200 feet of Cody shale. The rim rock consists of the basal sandstones and shales of the Mesaverde formation. Both formations are of Upper Cretaceous age, as are the productive sands of the Frontier formation, which underlies the Cody shale at a depth of 1,200–1,800 feet; however, the possibilities of lower producing horizons have not been fully explored. Underlying the Frontier, in descending order, are the Mowry and Thermopolis (Upper Cretaceous), the Cloverly (Lower Cretaceous), Morrison (Upper Jurassic), Sundance (Upper Jurassic), Chugwater (Triassic), Embar, Tensleep, Amsden, and Madison formations (Carboniferous). Hewett estimates that the Embar would be encountered at a depth of about 4,500 feet in the higher parts of the structure.

Structure.—Hewett[18] mapped two domes in this area separated by a low syncline or saddle with about 1,000 feet of closure at the top of the Frontier and designated them the East and the West Buffalo anticlines. Hintze[19] in 1928 mapped the structure in more detail. The map presented herewith (Fig. 3) is one submitted to the Geological Survey by the Midwest Refining Company in 1931, and revised by John G. Bartram of the Stanolind Oil and Gas Company in 1933. The structure maps from both sources show the East anticline as the higher. Hintze's map gives the East dome 200 feet more closure than the West dome, whereas the map here reproduced gives it only 100 feet more. The dip of the Mesaverde beds varies between 12° and 18° along the northeast flank of the folds and between 18° and 36° along the southwest flank.

Productive sands.—The production at present is only dry gas from the Frontier sands, sometimes referred to as the Torchlight and Peay sands, the Peay being the lower. Development of gas has been in progress since 1914, being carried on by the Midwest Refining Company (now Stanolind Oil and Gas Company) and the Ohio Oil Company. Until 1927, there was no demand for gas in this area and the wells were closed in. With the development of local demand for gas for power and domestic purposes production began in that year. The rock pressure is about 400 pounds per square inch and the initial production about 12,000,000 cubic feet per well although wells with a capacity of as much as 60,000,000 cubic feet have been completed. There are now 9 gas wells capable of production in the field.

[18] D. F. Hewett, *op. cit., Prof. Paper 145* (1926), Pl. II.

[19] F. F. Hintze, "Structure Map of Little Buffalo Basin," *Oil and Gas Journal*, Vol. 27, No. 41 (February 28, 1929), p. 41.

Lands involved.—Although negotiations for the unitization of Kettleman Hills were in progress at an earlier date, Little Buffalo Basin was the first unit project to be approved by the Secretary of the Interior under the act of July 3, 1930. On January 6, 1931, the Secretary approved an agreement providing for the unit operation of the field by the Midwest Refining Company and the Ohio Oil Company as limited by the 4,350-foot contour on the top of the first sand of the Frontier formation, embracing an area of 4,806.4 acres of which 81 per cent is Government land. The agreement applies only to gas from the Frontier sands and is effective as long as gas is produced from these sands. Each holding is allocated its share of the field production in the proportion that the productive area in such holding bears to the entire area within the 4,350-foot contour.

BIG SAND DRAW, WYOMING

Stratigraphy.—Collier[20] examined the area in reconnaissance in 1918. The northern part of the structure was examined in more detail by W. W. Boyer for the Geological Survey in October, 1926, and in the summer of 1928 Dobbin and Cronin examined the entire area for the purpose of revising the structure-contour map. According to Dobbin,[21] the youngest consolidated rocks in the field are the nearly flat sands, arkoses, and conglomerates comprising the White River formation, of Oligocene age. These comprise about 1,000 feet of strata and unconformably overlie the older formations at either end and on both sides of the structure. Beneath this formation lies the flat or slightly tilted Wind River formation (of Eocene age), which consists of about 1,500 feet of soft variegated shale, coarse brown sandstone, arkose, and conglomerate and is unconformable on older beds. About 800 feet of the sandstones, shales, and coal beds of the Mesaverde formation (Upper Cretaceous) are exposed at the north end of the field, the remainder of which is occupied by Steele shale, concealed for the most part by alluvium and wind-blown sand. The unexposed beds of the Upper Cretaceous series in descending order are the Steele shale, Niobrara shale, and Carlile shale, in all about 4,800 feet thick, together with about 1,125 feet of strata comprising the Frontier formation, Mowry shale, and Thermopolis shale.

Structure.—As described by Dobbin,[22] the Big Sand Draw anticline (Fig. 4) is a northward pitching, compressed fold with a steeply

[20] A. J. Collier, "Gas in the Big Sand Draw Anticline, Fremont County, Wyoming," *U. S. Geol. Survey Bull. 711-E* (1920).

[21] C. E. Dobbin, unpublished report on geologic map of the Big Sand Draw gas field, U. S. Geol. Survey, July 21, 1928.

[22] C. E. Dobbin, *op. cit.*, unpublished report, 1928.

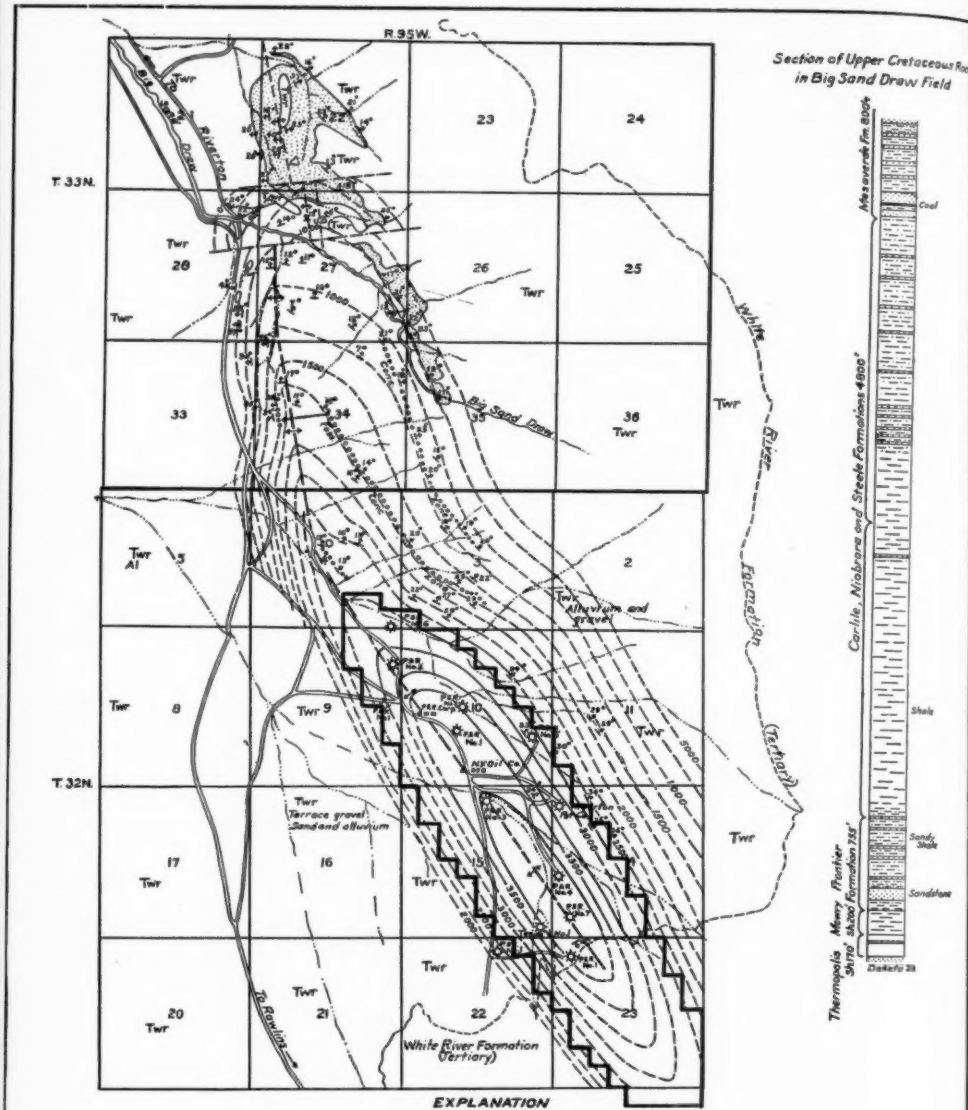


FIG. 4.—Structure-contour map of Big Sand Draw field.

dipping west limb. The slope of the east limb of the fold ranges between 22° and 36° but that of the west limb is not subject to observation by reason of the presence of unconformable younger beds on the Cretaceous formations. Near the north end of the structure the axis is offset toward the east by two parallel faults. The accompanying structure-contour map, resulting from the work of C. E. Dobbin and G. H. Cronin, indicates a closure of 1,600 feet at the top of the Frontier formation. Rae[23] has shown a similar amount of closure.

Productive sands.—The Frontier formation consists of 755 feet of alternating beds of fine-grained, gray sandstone, sandy shale, and shale. In January, 1918, the Producers and Refiners Corporation brought in the discovery well in the NE. ¼ of SW. ¼, Sec. 10, T. 32 N., R. 95 W., at a depth of 2,531 feet. The productive sands in the Frontier are found between the depths of 2,300 feet and 3,100 feet. The production ranges between 25 million cubic feet and 45 million cubic feet of gas, with rock pressures between 900 and 1,300 pounds per square inch. Gas has been encountered in a well drilled by the Producers and Refiners Corporation on the NW. ¼ of SW. ¼, Sec. 14, T. 32 N., R. 95 W., in sands correlated with the Muddy, from 3,400 to 3,430 feet; with the Dakota, from 4,218 to 4,232 feet and from 4,260 to 4,270 feet; with the Lakota, from 4,300 to 4,385 feet; and in one sand assigned to the Sundance formation, below a depth of 4,990 feet. The total depth of the well was 5,345 feet. Twelve productive gas wells have been completed.

Lands involved.—On February 11, 1932, the Secretary of the Interior approved a unit plan of development and operation applicable only to the deposits of natural gas in the area. Any leases issued are to remain in effect for a period of 20 years and beyond such period until the termination of said unit plan. The plan as approved affects a total of 1,960 acres operated by the Producers and Refiners Corporation, and includes 1,240 acres of Government land. The unitized area is bounded by the 2,750-foot contour and the agreement remains in full force and effect during the period of productivity of gas from the lands affected thereby. Each of the parties to the unit contract reserves his proportionate part, on an acreage basis, of the proceeds of the total gas produced and sold from that area in the proportion that the acreage interest within said area bears to the total unit area designated.

BILLY CREEK, WYOMING

Stratigraphy.—The areal geology of the Billy Creek region, Wyom-

[23] C. C. Rae, "Big Sand Draw Field, Wyoming," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12, No. 12 (December, 1928), p. 1144.

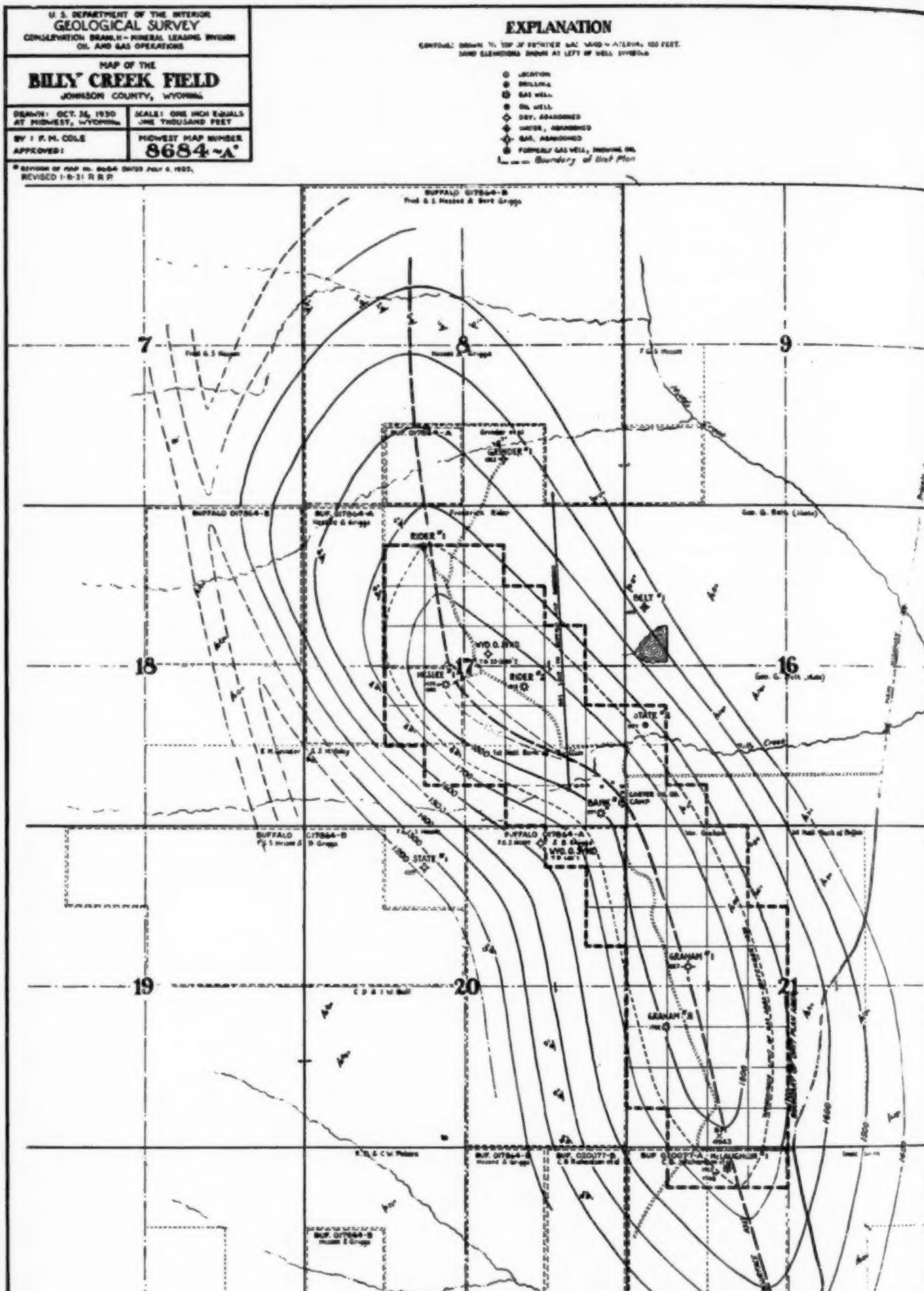


FIG. 5.—Structure-contour map of Billy Creek field.

ing, was mapped by Darton[24] between 1901 and 1903, but the nomenclature used in this paper conforms with that adopted for the *Geologic Map of Wyoming*, U. S. Geological Survey, 1925, and with the *Tentative Correlation of Geologic Formations in Wyoming* compiled by M. Grace Wilmarth, secretary of the committee on geologic names, published in April, 1925. Surface formations in and adjacent to the field consist in ascending order of the Steele shale, Mesaverde formation, Fox Hills sandstone, Lance formation, Fort Union formation, and Wasatch formation. Wells starting in the Steele shale (Upper Cretaceous) penetrate the Niobrara shale and Carlile shale before entering the gas sands of the Frontier formation, which carry a small amount of oil at depths between 3,100 and 3,300 feet. Tests have been drilled deeper into the Muddy sand of the Thermopolis shale, also of Upper Cretaceous age, into the Cloverly formation (Lower Cretaceous), and into the top of the Sundance formation (Upper Jurassic) at a reported depth of 4,786 feet.

Structure.—The formations dip away from the Big Horn uplift into the Powder River basin toward the east, with minor interruptions in the regional dip, as in the Billy Creek anticline, and with lessening inclination as the center of the basin is approached.

The accompanying structure-contour map (Fig. 5) was prepared by F. M. Cole of the Geological Survey from data supplied by the Carter Oil Company. According to Cole's interpretation of the structure, the Billy Creek anticline has about 500 feet of closure at the top of the Frontier gas sand. The anticline is approximately symmetrical, with flank dips on surface beds ranging between 8° and 12°. The area unitized is 0.5 mile wide and 2 miles long. It extends northwest and southeast along the axis and is limited approximately by the 1,750-foot contour.

Productive sands.—The Wall Creek sands of the Frontier formation are productive of gas, with minor amounts, 25 barrels to 100 barrels per well, of 20° A.P.I. oil. The Frontier sands are reached at depths between 3,100 and 3,300 feet. The deeper Muddy, Cloverly, and Sundance sands or their equivalents have been found dry. The capacity of the gas wells ranges between 30 million and 68 million cubic feet each and the rock pressure between 800 and 1,000 pounds per square inch. There are 7 productive wells in the field.

Lands involved.—The plan for unit development of the Billy Creek field, comprising 710 acres divided into 10-acre units, was approved by the Secretary of the Interior, April 11, 1932. The Carter Oil Com-

[24] N. H. Darton, *Cloud Peak—Fort McKinney Folio No. 142* (1906).

pany or its successor in interest is the operator of the field, and the plan applies only to deposits of gas from sands of the Frontier formation.

Land Status	*Acres*	*Per Cent of Total Area*
Fee	560	78.9
United States	110	15.5
State	40	5.6

The plan remains in full force and effect during the term of commercial productivity of gas from the unit area. The value of gas or gasoline produced and sold is allocated to the respective title holders in proportion to the number of 10-acre units held within the unit plan area as compared with the total number of such units in the unitized area.

PITCHFORK, WYOMING

Stratigraphy.—The Pitchfork anticline (Fig. 6) in Park County, Wyoming, was examined in 1915, by Lupton,[25] who suggested that the anticline might be productive of oil and gas. The lower part of the Mowry shale (Upper Cretaceous) is exposed along the crest of the anticline. Underlying the Mowry is 400 to 500 feet of shale correlated by Lupton with the Thermopolis shale (Upper Cretaceous), containing the Muddy sand. Beneath the Thermopolis is the Cloverly formation (Lower Cretaceous) containing the Greybull sand at its top. Underlying the Cloverly, in descending order, are the Morrison, Sundance (Jurassic), Chugwater (Triassic), Tensleep, Amsden, and Madison (Carboniferous) formations. A well completed by the California Exploration Company on the NW. $\frac{1}{4}$ of NE. $\frac{1}{4}$, Sec. 14, T. 48 N., R. 102 W., reached the top of the Amsden formation at a depth of 3,903 feet.

Structure.—The accompanying contour map (Fig. 6) showing structure on top of the Mowry shale was submitted with the unit-development contract which was approved by the Secretary of the Interior. The Pitchfork anticline is a narrow, asymmetrical, arcuate anticline about 3 miles long and 0.5 mile wide. The west limb is the steeper and is broken by several faults. The axial shift with depth is indicated by the heavy black line designated "Tensleep axis" on the map, and the "red line" (inner line) approximates the 2,200-foot contour on a sand in the Tensleep formation.

Productive sands.—On November 30, 1930, the California Exploration Company completed the only productive well on the structure,

[25] D. F. Hewett and D. T. Lupton, "Anticlines in the Southern Part of the Big Horn Basin, Wyoming," *U. S. Geol. Survey Bull. 656* (1917), pp. 171–73.

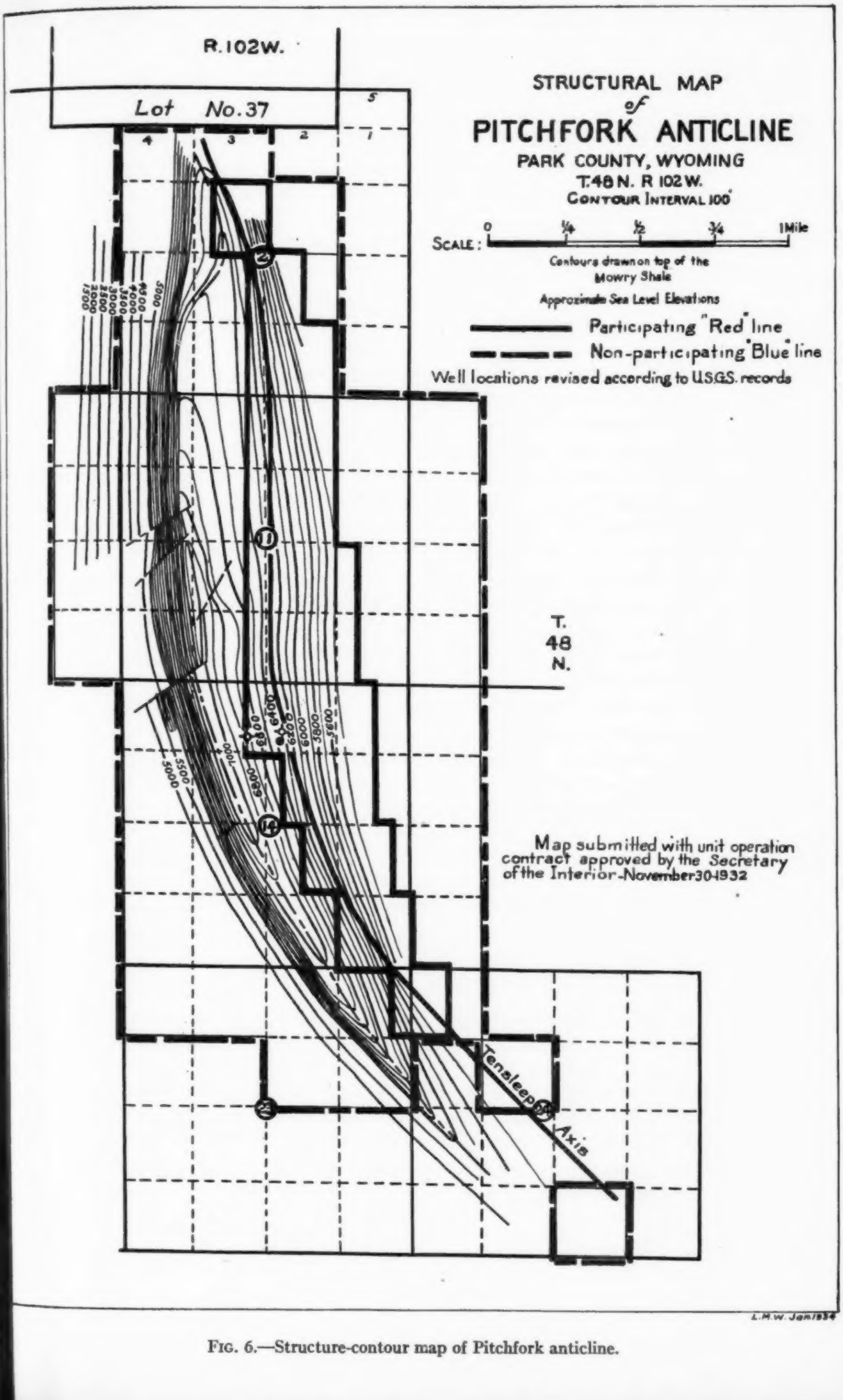


FIG. 6.—Structure-contour map of Pitchfork anticline.

on the NW. ¼ of NE. ¼, Sec. 14, T. 48 N., R. 102 W., at a total depth of 3,903 feet, with an initial daily production of 434 barrels of black oil of 18.6 A.P.I. gravity. Production was found in sands in the Embar formation from 3,350 to 3,356 feet and from 3,420 to 3,450 feet, and in the Tensleep formation from 3,600 to 3,615 feet, and from 3,743 to 3,782 feet. The Greybull sand in the Cloverly formation, in which a small amount of gas has been found, is the only one of the shallower sands which carries hydrocarbons, according to reports from the field.

Lands involved.—On November 30, 1932, the Secretary of the Interior approved a unit plan of development and operation for the Pitchfork structure involving approximately 2,564 acres, all public land. This plan contemplates joint development of the field by the California Exploration Company and the Producers and Refiners Corporation as operators. The area within the "red line" (inner line) comprises about 570 acres and is bounded approximately by the 2,200-foot contour on the top of a sand in the Tensleep formation.

The area within the red line is never to be reduced but it may be expanded should subsequent drilling prove an additional area productive. This is the participating acreage. The "blue line" (outer line) delineates the outer boundaries of the area covered by the agreement and this area may be expanded with the consent of all parties to the contract. The land between the red and the blue lines is designated as nonparticipating acreage. The production from any and all lots, pieces or parcels of the participating acreage, is allotted equally to each 10-acre tract thereof. The contract remains in full force and effect as long as oil or gas is produced.

UNIT PLANS AS RELATED TO GEOLOGY

Regardless of the procedure employed to effect unit or coöperative plans of development in the past, the geologist must be consulted before any scientific or equitable plan can be formulated. Failure of companies to avail themselves of competent geological advice may lead to hopeless complications and needless expense in perfecting an agreement equitable to all parties concerned. Although geologists frequently differ as to details, they generally agree on fundamental principles and the fact remains that differences of opinion as to detail seldom result in material variations of judgment as to the total area that is properly subject to inclusion in a unit plan. The writers therefore are firm in the belief that reliable geological information is essential to the equitable operation of any plan of unit or coöperative development.

STRUCTURAL CONDITIONS INDETERMINABLE

Where structures are concealed beneath unconformities, where pools exist because of some condition other than structure, or where the surface expression is vague or impossible of accurate interpretation by geophysical or ordinary geological methods, the geologist's opinion concerning lands properly subject to unitization is unquestionably superior to any guess made by one not conversant with scientific principles. In regions where folds are not evidenced by surface formations, administrative practice in dealing with holders of prospecting permits on public land has been to consider a test well in the center of a circumscribed square each of whose 6-mile sides is 3 miles in a cardinal direction from said well, as technically competent to affect lands within such square. The total area involved in such a case is approximately 23,000 acres. It is frankly admitted that no definite rule can be laid down for a determination of logical unit boundaries under circumstances of this sort, inasmuch as infinite variations and combinations of conditions are possible. It is evident, however, that regardless of structural obscurity the judgment of a competent geologist is the best that can be applied to such a problem.

A delineation of probable productive area in advance of development where a discovery of oil or gas indicates that the accumulation may be due to lensing reservoir rocks, to variations in porosity, to concealed faults, or to unconformities, constitutes the most difficult type of case confronting the geologist who has the responsibility of recommending the area to be segregated as a unit. Under these circumstances his decision cannot be other than arbitrary but it will incorporate his knowledge of structural habit in the region involved and of analogous conditions noted by him elsewhere or described in the literature of his profession.

STRUCTURAL CONDITIONS DETERMINABLE

Where structural conditions are apparent an agreement as to the total area to be included in the unitized project is not difficult of consummation. The majority of known producing fields of which the structure is evident fall under the following classification or modifications thereof.

- Monoclines[38]
- Anticlines or domes
  - Symmetrical
  - Asymmetrical

[38] For the purpose of administration of the public land laws no distinction is made between monoclines and homoclines.

Monoclines.—Thus far no unit project involving monoclinal accumulation of oil or gas has come to the attention of the Geological Survey. However, the principles determining the unit area would be similar to those discussed below in connection with anticlinal folds, and the selection of acreage in advance of development would be governed to a considerable extent by experience in similar areas already developed. The procedure employed by the Geological Survey in outlining the "known geologic structure" of a producing oil and gas field under the leasing-law regulations approved March 11, 1920 (General Land Office Circular No. 672), suggests methods applicable in outlining the gross area to be segregated for unit or coöperative development. The structure-contour map is the primary basis of such action.

Anticlines.—For anticlinal fields the axis of a limiting syncline is obviously the extreme outer limit of acreage over which administrative jurisdiction might be desirable for purposes of unit operation. Patently, all lands within such extreme limits can not be expected to prove productive, but until the limits of productivity are actually established by drilling an ample acreage margin of safety is desirable. This procedure, however, is not to be confused with that employed in defining "known geologic structure" for purposes of leasing-law administration. For partly developed anticlinal fields, Survey practice in outlining "known geologic structure" is to include lands within the lowest closing contour which embraces a known edge well or within which it may be assumed on available evidence that a productive well may ultimately be drilled. More than 122 fields involving Government lands in the western states have been defined by the Geological Survey in accordance with the law and regulations cited.

In outlining a proposed unit area covering a symmetrical anticline the geologist would be governed by the considerations indicated above. Examples of this type appear in the accompanying figures. In effect, the outer boundary of a unitized area may include both proved and probable oil or gas territory; in other words, "participating" and "nonparticipating" lands, respectively.

Where a proposed unit development covers an asymmetrical anticline, or variations of that type of folding, an accurate outline of the area in advance of extensive development is difficult. The Pitchfork anticline (Fig. 6) is an example of this problem. The participating area (inner line) was determined by geologists of the companies involved and represents the probable producing area on the top of a sand in the Tensleep formation at a depth of about 3,600 feet.

The interpretation of the structure of the McCallum anticlines by

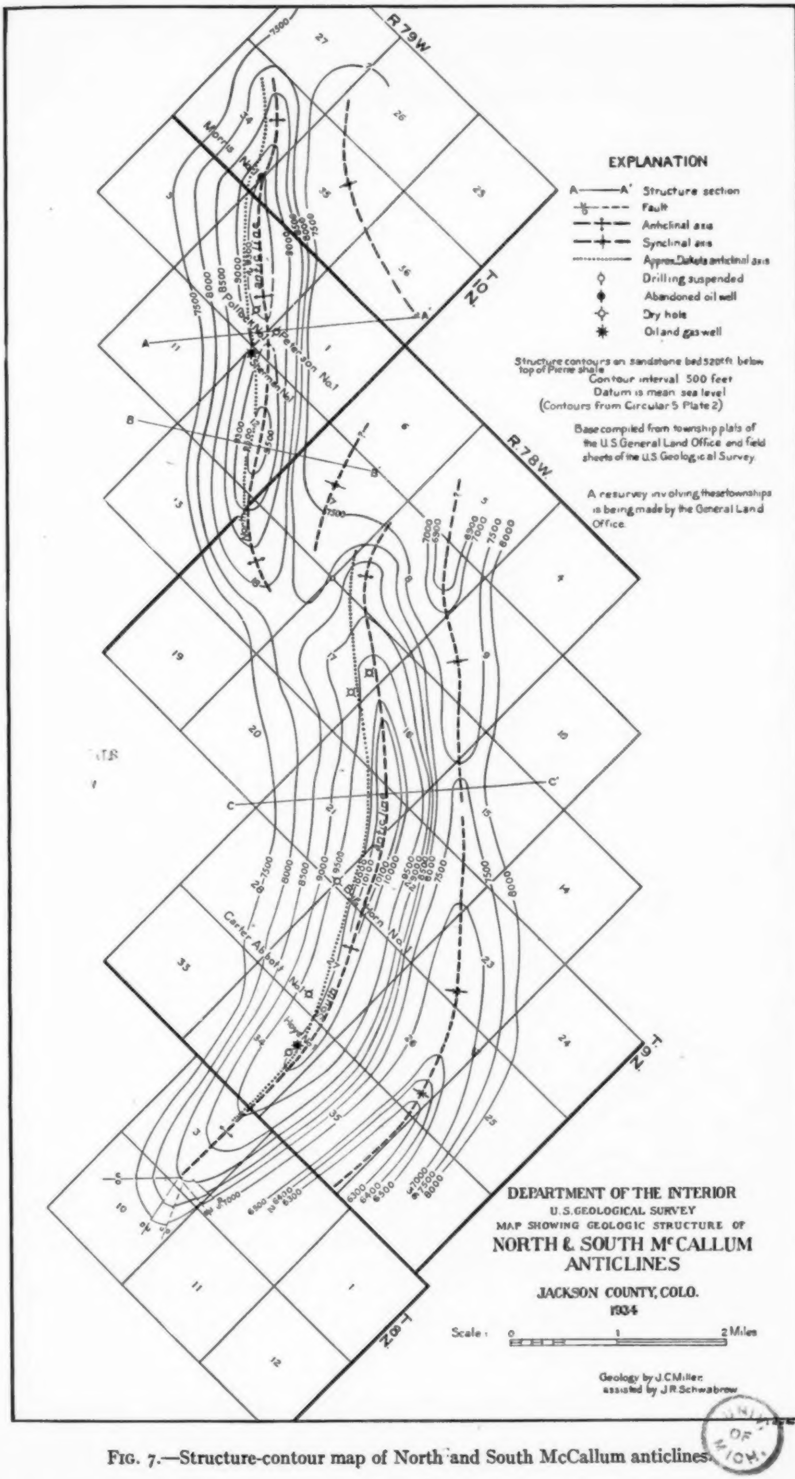


FIG. 7.—Structure-contour map of North and South McCallum anticlines.

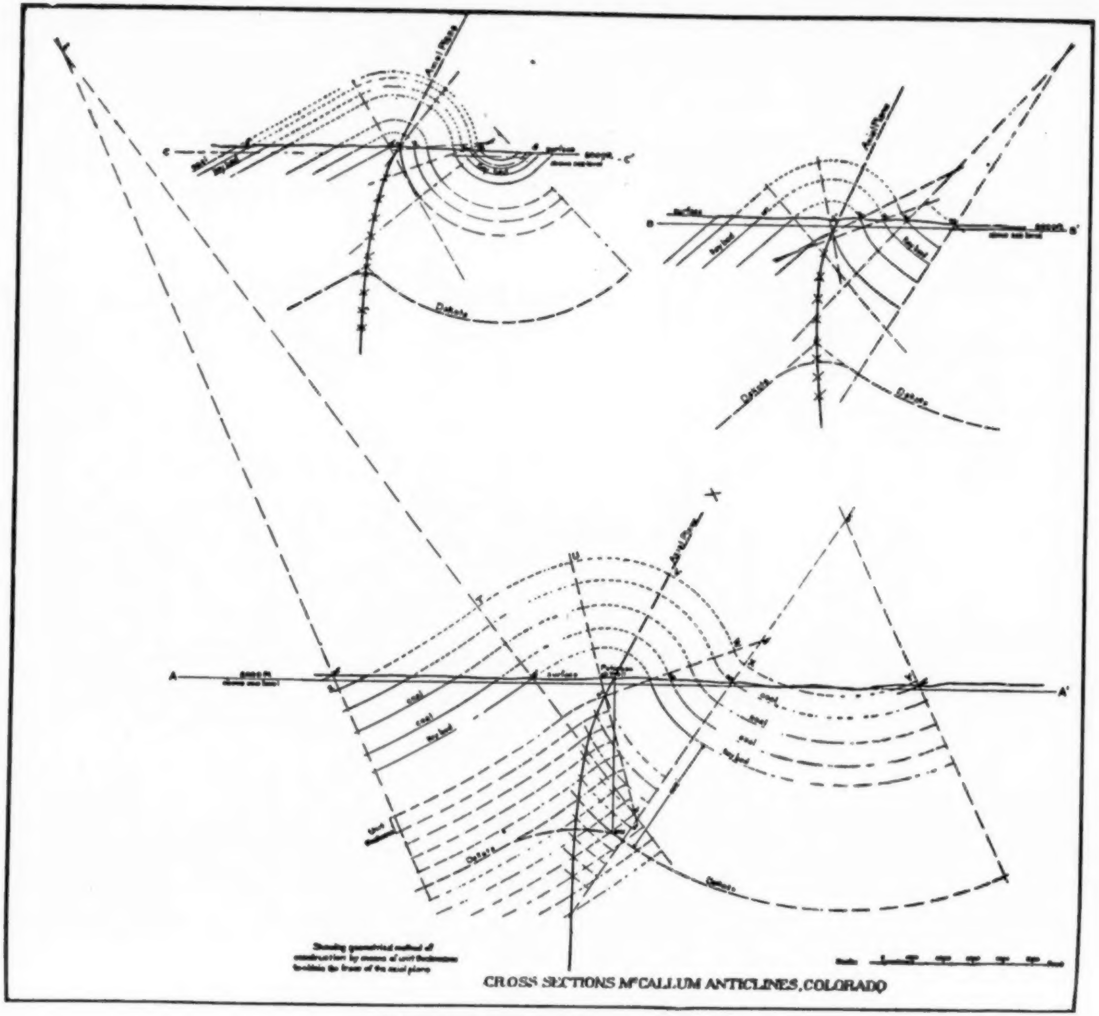


FIG. 8.—Cross sections of McCallum anticlines.

the co-writer[27] of this paper, shown on Figure 7, further exemplifies the problems of asymmetric folds. For this area a unit development is contemplated and, inasmuch as the producing sand (Dakota) lies at a depth of about 5,000 feet in the wells shown, a determination of the probable crestal area is vital. The maximum shift with respect to land lines, of the crest of the fold in the Dakota sand toward the side of lesser dip, represented by the line of heavy dots on Figure 7, is about ¼ mile. It is to be noted, however, in the cross sections shown (Fig. 8), that, according to construction, the axial plane does not necessarily intersect the crest of the anticline. Busk[28] has developed a series of geometrical propositions a few of which were used in the preparation of these cross sections. The surface anticlinal axis shown on Figure 7 represents the trace of the crestal plane rather than that of the axial plane. Busk's method, when competent folds are assumed, briefly stated, consists of constructing normals to the dips and of using their points of intersection as the centers of arcs representing the folded strata. Unit thicknesses are marked off along the radii, and successive arcs are described. The axial plane or surface is drawn in by joining the apices of the units of thickness represented with a smooth curve. While the representation of such steep folds in cross section involves under certain conditions factors not determinable from field investigation, particularly in areas where there has been an appreciable amount of squeezing and flowage of beds, the method affords a means of obtaining a more or less hypothetical subsurface structure-contour map by graphic methods. The result is admittedly no exact representation of subsurface structure but serves as a form of insurance against omitting from a unit plan lands which later may prove to be productive. The greater the depth to the productive sand the greater is the risk of including nonproductive acreage in the "participating" area. Under these conditions it is therefore necessary for the geologist to make use of the meager information sometimes furnished by surface investigations prior to development in order to make proper recommendation to the land and legal departments.

The cross sections developed (Fig. 8) illustrate the economic importance of a proper determination of crestal area on the producing sand in regions where the folds are more or less pronounced and the depth to the sand is 5,000 feet or more. It is apparent that a mere

[27] J. C. Miller, "Geology of the North and South McCallum Anticlines, Jackson County, Colorado, with Special Reference to Petroleum and Carbon Dioxide," *U. S. Geol. Survey Circular No. 5* (1934).

[28] H. G. Busk, *Earth Flexures, Their Geometry and Their Representation and Analyses in Geological Section*, Cambridge University Press (1929).

straight-line projection of the axial plane or of the crestal plane in section, namely a plane through the so-called anticlinal axis, may lead to divergent results depending on the magnitude of overturn or lack of symmetry of the fold. From the construction illustrated by the cross sections on Figure 8, it is seen that the higher part of the anticline lies to the left of the axial plane, whereas a projection of the surface crestal plane, especially in the absence of geometrical construction similar to that here employed, would result in the location of the crest of the subsurface structure nearly 1,000 feet from its determined location. Regardless of whether one uses Busk's methods or the graphic or mathematical methods for determining thicknesses developed by Hewett,[29] Mertie,[30] Rubey,[31] and others, the significant objective is the area on the crest of the subsurface structure that is occupied by the producing sand and its surface translation into subdivisions of the public-land survey. This determination, of course, is advantageous and of importance principally in advance of development.

The participating acreage outlined on the accompanying maps is considered as proved oil land and participates in the profits accruing to the association or to the operator. In most of these instances provision has been made in the unit agreement for expansion of the boundaries of participating acreage if and when additional acreage proves productive, such additions being in 10-acre units.

ADMINISTRATIVE FEATURES

Laws and regulations.—The first permanent Federal legislation permitting unit operation was the act of March 4, 1931 (46 Stat. 1523) amending sections 17 and 27 of the mineral leasing law of February 25, 1920 (41 Stat. 437). This act as amended provides:

> That for the purpose of more properly conserving the natural resources of any single oil or gas pool or field, permittees and lessees thereof and their representatives may unite with each other or jointly or separately with others in collectively adopting and operating under a coöperative or unit plan of development or operation of said pool or field, whenever determined and certified by the Secretary of the Interior to be necessary or advisable in the public interest. . . .

[29] D. F. Hewett, "Measurements of Folded Beds," *Econ. Geol.*, Vol. 15, No. 5 (1920), pp. 367–85.

[30] J. B. Mertie, Jr., "Graphic and Mechanical Computation of Thickness of Strata and Distance to a Stratum," *U. S. Geol. Survey Prof. Paper 129-C* (1922).

[31] W. W. Rubey, "Determination and Use of Thicknesses of Incompetent Beds in Oil Field Mapping and General Structural Studies," *Econ. Geol.*, Vol. 21, No. 4 (June–July, 1926), pp. 222–351.

Since April, 1932, oil and gas prospecting permits have contained provisions for the submission of an acceptable unit plan of prospecting and development of the field and compliance with State and Federal laws or regulations concerning proration or allotment of production. Extensions of time on older permits are now granted with similar provisions. The authority of the Secretary is limited under section 17 (amended) to modification of the quantity and rate of production under a unit plan, to suspension or modification of drilling requirements, and to reduction of the royalty on future production whenever the average daily production of any oil well shall not exceed 10 barrels per day. Under section 27 the Secretary is empowered to establish, alter, change, or revoke drilling, producing, and royalty requirements of leases included in a unit plan with consent of the lessees and permittees whenever it is necessary or desirable in the public interest. This gives the Secretary broad discretionary power and permits, for example, a change of royalty rates from the sliding scale to the flat rate similar to existing commercial leases.

Maps.—These regulations also provide for the submission of certain geological data in applications for coöperative or unit plans of development or operation of oil or gas pools or fields, as follows.

Such application should be in the form of an agreement, contract, or plan, and should be supported by structure and ownership maps and papers necessary to a complete understanding of the proposed development.

Provision is further made that

Upon request by parties interested for the bona fide purpose of formulating a coöperative or unit plan, the area logically subject to unitization will be designated by the United States Geological Survey.

The use made of this proffered service or of any resulting suggestions is entirely optional with the permittee or lessee. Any structure-contour, fault, combination of structural boundaries, or any arbitrary line mutually agreed upon by the parties in interest based on geological findings, Federal or otherwise, may be selected as a unit boundary.

Agreements.—In all except one of the fields discussed "unitization" has followed discovery. However, tentative or preliminary unit plans may be submitted for approval covering areas in which discovery of oil or gas has not been made, such as the South dome of the Kettleman Hills. In such cases the desirable plan is to formulate an agreement for purpose of prospecting with provision for subsequent determination of participating and nonparticipating acreage.

Unitization as contemplated by the departmental regulations approved April 4, 1932, is understood in the Geological Survey to comprehend any agreement, satisfactory to the Secretary of the Interior, providing for the exploration and development of the Federal and State and private lands involved in accordance with a specified operating plan equitably allocating the costs and the production to those lands.

No definite form of agreement, contract, or plan for the unit operation of fields containing Government lands has been formulated, although suggestions have been offered for the guidance of applicants contained in instructions and information circulars[32] issued by the Department of the Interior.

The relative rights and obligations of the various parties in interest under a unit plan should be clearly shown in the initial agreement accompanied by a simple statement of their extent and the conditions of their termination. Naturally these will vary greatly between different units, but in most instances they will reflect the ratio borne by the acreage of the participant to the entire acreage unitized. Unitization in its simplest form concedes to all productive acreage within the areal limits of the same common reservoir identical proportions of the production obtained. The type of reservoir and the number of wells necessary to drain it are primary considerations in formulating the provisions and regulating the amount and duration of participation of acreage held by the parties in interest.

In the main the essentials to be included in the plan are guarantees giving the Secretary authority to exercise the mandatory requirements under the acts cited such as drilling, producing, and royalty provisions under leases and permits. In addition a provision accepting all State and Federal conservation laws, regulations, and orders must be included.

CONCLUSIONS

The importance of petroleum, emphasized by the World War, as a basis for national power and security since it is one of the chief sources of energy used in production and distribution, naturally led to consideration of measures of conservation by the Government. With the productive capacity of the industry increased vastly beyond national peace-time demand, coupled with scientific developments tending to increase that supply, and faced with an increasing foreign

[32] *Mimeograph No. 63034*, "Coöperative or Unit Plan of Development of a Single Oil or Gas Pool or Area," under the act of March 4, 1931 (*46 Stat. 1523*), Departmental Instructions June 4, 1931 (*Circular 1252–53 L. D.*), and Departmental Regulations April 4, 1932 (*53 L.D.*).

production, leaders in the petroleum industry have been forced to consider methods of controlling production. The effect of overproduction on prices is well known but the general public is not aware of its ultimate cost; nevertheless, those in the petroleum industry know only too well the energy wasted in unscientific methods of development and production. Certainly, unit operation is a milestone in the progress of the petroleum industry and splendid evidence of economic coöperation in the public interest. To the geologist rightfully devolves the fundamental task of its initiation.

It scarcely needs to be stressed that the important subsequent work of the petroleum engineer, that is, production control, full utilization of reservoir energy, economic spacing of wells, flooding, repressuring, and other conservation measures, a discussion of which is beyond the scope of the present paper, is made easier of accomplishment through unit or coöperative development of a single field or geologic structure.

DISCUSSION

C. V. MILLIKAN, chairman, Tulsa, Oklahoma: I think we all recognize that there are many advantages in unit operation. The Government has taken a leading step in this direction. Any questions you have concerning policies Mr. Avery will be glad to answer.

JOHN G. BARTRAM, Casper, Wyoming: The attitude of the United States Government, through the Geological Survey in Wyoming and Rocky Mountain fields, has advanced the principle and application of unit operation a great deal, but I want to point out in this connection that Kettleman Hills unit operation is somewhat different from the ones that have been outlined in Wyoming. The Wyoming operators have put into effect unit operation in several fields, either fields in which the limit of the field has been reasonably well defined by wells already drilled, or fields in which all of the lands were largely controlled by one operator. The reason there are not more unit operations in Wyoming, on areas that are partly Government land and partly State land, is because in other fields the operators and geologists do not know the limits of the producing fields and the different interested parties have been unwilling to sign contracts when they did not know whether their lands were productive or not. On the Kettleman Hills unit operation they entered into an agreement that provided for the reclassification of the land between the possible area and the proven area.

G. C. GESTER, San Francisco, California: As the contract was first drawn up at Kettleman Hills there were two lines established, the outer blue line and the inner red line. The area within the red line was considered proven and this line could not be contracted. The acreage within the blue line was classed as participating acreage and was subject to change. These lines were determined at a time when there were comparatively few geological data and the limits of production could not be actually outlined with any certainty. It is provided in the unit agreement that certain outpost wells, or wells to determine the outer limit of production, should be drilled. As these wells are drilled

and new information obtained from them, such data are to be used in a form of reclassification of the lands between the red and the blue lines. Once a year, I believe, there is a committee which meets to study this problem and to advise the board of directors, and said board by at least a two-thirds vote shall determine what acreage between the red and blue line is non-productive. The unit agreement went into effect in 1931 and in 1932 there was no reclassification. In February, 1933, because of wells drilled and new data obtained, the board was able to revise the map and has accordingly extended the proved limits considerably beyond the red line, particularly toward the northwest, but still well within the outer blue line. Similarly, in February, 1934, the committee again met and as a result of their deliberations there has resulted what is termed the "purple line." Comparatively little change was made in the brown line, there being some extension, however, toward the northwest.

C. V. Millikan: Unit operation in Kettleman is not limited to the Temblor?

G. C. Gester: Not entirely, although in the consideration that was given to the change of the brown and purple lines it was recognized by the committee that there were possibilities that a productive zone might be developed by the so-called Lillis-Welch well at the extreme northern end of the Kettleman Hills. This zone would be considerably deeper and older than the Temblor. Although some oil and gas have been encountered in this zone, commercial production has not been established and it was decided to withhold any action on this matter until some later meeting after further data had been obtained. It is my understanding that a consideration of the possibilities of deeper zones is contained in the general plan and that that possibility is so taken care of that a new plan will not have to be developed in the event of the discovery of new deep zones.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 11 (NOVEMBER, 1934), PP. 1493-1505, 3 FIGS.

FOSSIL SINK HOLES IN CRETACEOUS BEDS OF PROWERS COUNTY, COLORADO[1]

CARLE H. DANE[2] AND W. G. PIERCE[2]
Washington, D. C.

ABSTRACT

In a small area in Sec. 6, T. 22 S., R. 44 W., Prowers County, Colorado, there are three roughly circular areas from 100 to 200 feet in diameter in which collapsed and brecciated masses of the Hays limestone member and Smoky Hill marl member of the Niobrara formation occur in contact with the uppermost part of the underlying Carlile shale. They are probably exhumed sink holes formed as a result of the development of solution caverns within the Greenhorn limestone or within soluble horizons in deeper lying rocks. As a result of repeated roof subsidence such caverns may have worked their way upward through the overlying rocks by a process of natural stoping, probably during Pleistocene time. The exposures now observed represent cross sections of the natural stopes at levels somewhat below the height they originally reached.

INTRODUCTION

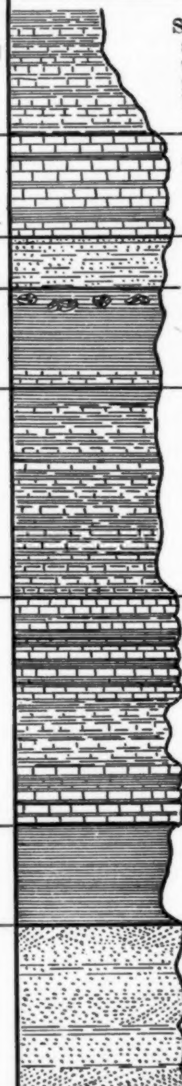
In a small area in Prowers County, Colorado, the exposed Upper Cretaceous rocks are locally disturbed in a way which indicates the former presence of three sink holes. The occurrence of these features is of more than ordinary interest, because they may exemplify conditions which exist at lower levels of the subsidences that have caused abrupt sinking of the ground at many places in western Kansas[3] within the period of historical record.

The locality to be described is in Sec. 6, T. 22 S., R. 44 W., about 20 miles west of the Colorado-Kansas State line and about 4 miles north of Arkansas River. It may be reached by a road north along the west side of R. 44 W.

[1] Manuscript received, March 29, 1934. Published by permission of the director, United States Geological Survey.

[2] United States Geological Survey.

[3] W. D. Johnson, "The High Plains and Their Utilization," *U. S. Geol. Survey Twenty-First Ann. Rept.*, Pt. 4 (1901), pp. 705–12.
R. C. Moore, "Note on Subsidence near Sharon Springs, Wallace County, Kansas," *Kansas Geol. Survey Bull. 11* (1926), pp. 95–96.
W. L. Russell, "Local Subsidence in Western Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 6 (June, 1929), pp. 605–09.
M. K. Elias, "Origin of Cave-ins in Wallace County, Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 3 (March, 1930), pp. 316–20.
N. W. Bass, "Recent Subsidence in Hamilton County, Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 2 (February, 1931), pp. 201–05.
M. K. Elias, "The Geology of Wallace County, Kansas," *Kansas Geol. Survey Bull. 18* (1931), pp. 224–36.
K. K. Landes, "Recent Subsidence, Hamilton County, Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 6 (June, 1931), p. 708.



Formation	Member	Lithologic character	Thickness (Feet)
Niobrara formation	Smoky Hill marl	Soft shaly yellow chalk, chalky shale, and shale (top not exposed; the thickness given is the approximate total thickness of the member).	700±
	Hays limestone	Thick-bedded cream-colored chalky limestone with thin partings of gray shale.	65
Carlile shale	Codell sandstone	Sandy shale and earthy sand with a hard gray, slightly sandy limestone at the top.	30
	Blue Hill shale	Black fissile noncalcareous shale with a zone of large septarian concretions in the upper part.	60
	Fairport chalky shale	Calcareous and chalky shale with thin limestone beds.	125
Greenhorn limestone		Alternating beds of platy gray and white limestone and gray calcareous shale in the upper and lower parts, with a middle part consisting largely of gray calcareous shale.	135
Graneros shale		Dark-gray fissile shale.	60
Dakota sandstone		Irregularly bedded and cross-bedded light-colored sandstone, for the most part cemented hard, and some sandy shale and shale.	100±

FIG. 1.—Generalized stratigraphic section of Upper Cretaceous rocks exposed in Prowers County, Colorado.

DESCRIPTION OF EXPOSURES

The accompanying columnar and stratigraphic section (Fig. 1) summarizes the lithologic character and thickness of the succession

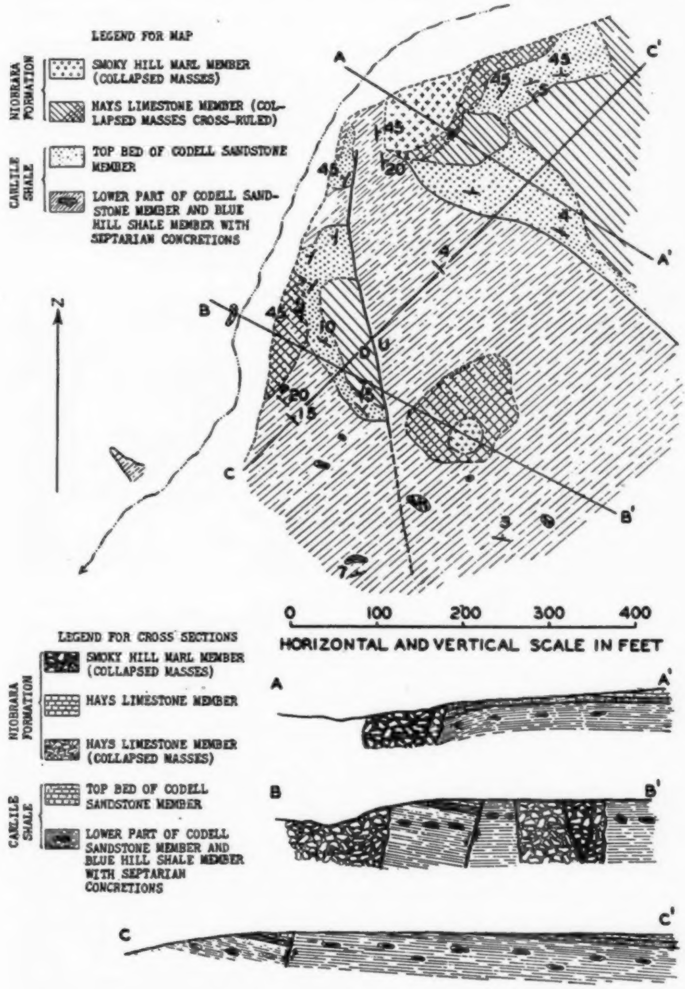


FIG. 2.—Geologic map and interpretative cross sections of sink-hole area in Sec. 6, T. 22 S., R. 44 W., Prowers County, Colorado.

of the Upper Cretaceous rocks which crop out in the region. The terminology is that which we have recently adopted.[4] Bass[5] has given a detailed description of the stratigraphic succession in Hamilton County, Kansas, which adjoins Prowers County, Colorado. The succession of rocks there is closely similar to that exposed in the part of Prowers County north of Arkansas River.

The geology of the sink hole area shown in Figure 2 was mapped on a scale of one inch to 100 feet. The top hard bed of the Codell sandstone member was differentiated on the map to make the struc-

FIG. 3.—Collapse breccia of Hays limestone member of Niobrara formation in contact with uppermost part of Carlile shale at right.

ture clearer. Parts of the map without line pattern represent areas partly concealed by alluvium of the small creek or by slope wash, and also areas of regular structure. There are shown three areas of subsidence, which are between 100 and 200 feet in diameter and from 150 to 250 feet apart. Brecciated masses of the Hays limestone member of the Niobrara formation occur in all three of the subsidence areas. Collapsed and brecciated masses of the Smoky Hill marl member of the Niobrara formation occur in the central parts of two of the subsidence areas. The Smoky Hill is identifiable both by its lithology and by the occurrence in it of a characteristic fossil, *Inoceramus grandis*. These collapsed masses are in contact with the uppermost part of the Carlile

[4] C. H. Dane and W. G. Pierce, "Geology and Oil and Gas Prospects in Part of Eastern Colorado," *U. S. Dept. Interior Press Mem. 72215* (June 8, 1933).

[5] N. W. Bass, "Geologic Investigations in Western Kansas, Pt. 2, Geology of Hamilton County," *Kansas Geol. Survey Bull. 11* (1926), pp. 59–76.

shale which normally underlies the Niobrara formation. Some of the collapse filling has thus dropped more than 65 feet, the thickness of the Hays limestone member.

The breccia consists of rounded and angular pieces ranging in size from very small fragments to large blocks several feet through. The larger pieces are either solid or, more generally, shattered by numerous joints, an intervening stage toward their breaking up into smaller pieces (Fig. 3). These features are better shown by the more brittle Hays limestone, whereas the softer Smoky Hill marl so weathers that the outlines of individual blocks are less clearly revealed.

The marginal belt of the northernmost sink clearly shows drag into the area of greatest subsidence. This is also shown by part of the eastern margin of the southwestern sink. The southeastern sink shows the shattered Smoky Hill marl member in the central part, with similar shattered masses of the Hays limestone member around it, and for a short distance along the northwestern edge an exposure of the top bed of the Codell sandstone member has a vertical dip. This is the relationship one would expect if the beds collapsed into an underlying void. Naturally, very little of the side walls of the sinks can be observed; a vertical distance of about 10 feet of the side wall of the southwesterly one is exposed where the ground surface slopes abruptly down to the alluvial flat of the small creek. The side wall there appears to be nearly vertical, though it perhaps inclines slightly toward the center of the collapsed mass.

The dip of beds in the Blue Hill shale in the immediate vicinity of the sinks is from 2° to 5° somewhat to the east of north. This direction of dip is also shown by the Fairport chalky shale member of the Carlile shale which crops out several hundred feet farther south. The beds shown on the map, however, are cut by a small normal fault with steep dip, which drops the beds on the west side probably not more than 20 feet. This fault terminates toward the south by diminishing throw, and toward the north by change into a steep westerly dip. Slickensides on the fault surface are vertical and some of the vein calcite filling is also thus slickensided, showing that there was at least some repetition of movement on the fault.

ORIGIN

It appears that the structural features observed are not to be explained as due to the operation of erosional processes at the surface that are related to the position of the small creek. The southeastern sink is located on a nearly level flat 20 feet above the present level of the creek and not associated with any recognizable former course of

the creek. The exposure of shattered masses at the creek level, moreover, shows that the features could not have originated as surficial slump or talus, unless the creek had at one time cut considerably deeper than its present level and subsequently refilled its old channel. This possibility is excluded by the fact that the stream is cutting on bed rock a short distance upstream and known to be only a few feet above bed rock downstream. Perhaps more conclusively, outcrops of the Smoky Hill member, which is present in the central parts of two of the sinks, do not now occur within a distance of perhaps two miles, evidently having been stripped back during a long interval of erosion since the collapse occurred.

As one of the sinks is demonstrably circular in plan, it suggests that the other two are also, although the outcrop evidence of their form is partly concealed by the surficial mantle. It seems, therefore, that their origin is to be attributed to removal of material from below and subsequent or concomitant collapse into the void thus created.

The "sink holes, or swales, or lagoons" of the Tertiary plains of western Kansas were attributed by Haworth[6] to a "natural settling process" operating on heterogeneous Tertiary materials. He believed that the formation of original slight depressions led to an accumulation of water which by downward percolation carried away a greater amount of material than would be dissolved elsewhere. Haworth also suggested that the principal part of erosion in the headward portions of arroyos on the plains was accomplished by a slow creeping of underground soils beneath the surface.

Crescentic sod-cracks and the low scarps developing from them in gullies in the semi-arid western plains have also been explained as probably due to the abstraction of material within the zone of moving ground water by the washing out of clay particles from the soil and subsequent settling and compacting over the places from which some material has been removed.[7] We have observed the results of the operation of this or a similar process in areas of bad-land exposure of mudstone in northwestern New Mexico where inverted conical depressions in the soft clayey surface drain into channelways below. It is not impossible that some such process operating in the Carlile shale might produce voids into which the overlying harder beds would eventually collapse. On the whole, however, the phenomena mentioned seem to occur near the surface of the ground and to require

[6] Erasmus Haworth, *Physiography of Western Kansas*, Univ. Geol. Survey of Kansas, Vol. 2 (1897), pp. 18–20.

[7] W. W. Rubey, "Gullies in the Great Plains Formed by Sinking of the Ground," *Amer. Jour. Sci.*, Vol. 15, No. 89 (May, 1928), p. 421.

either an outlet to the surface for the material washed out in suspension or a loose-textured medium through which the ground-water circulation could continue to carry finer-sized particles. The immediately underlying Carlile shale does not fulfill this last requirement. Nor do there appear to be any surface outlets near by to permit the removal of the material at a level below the lowest exposures of collapsed material. We believe, therefore, that the cause of the Prowers County sinks must be sought in the formation of caverns at some horizon within the more deeply underlying sedimentary rocks.

It has been long believed that some of the sink holes and larger depressed areas on the High Plains of western Kansas are due to removal of soluble masses of salt and gypsum from the Permian rocks,[8] either where they are covered directly by Tertiary beds or where a relatively thin section of Cretaceous beds intervenes. Johnson, however, in his study of the High Plains and their utilization, rejected caving due to removal of soluble material from the Cretaceous rocks as a cause of any basin depressions on the High Plains, because many of them occur where Cretaceous rocks, mostly sandstones and shales to great depth, underlie the Tertiary beds.[9] But within the past 10 years abrupt sinking of the ground, producing steep-sided holes and basins in Wallace and Hamilton Counties, Kansas, has been regarded by some as the surface expression of the formation of solution caverns within the Cretaceous rocks.

Moore[10] offered the following explanation for the subsidences in Wallace County, Kansas.

> The structural relationships of the Cretaceous rocks show that water entering the Niobrara in eastern Colorado may be expected to migrate down the dip to this soluble and more or less porous formation, emerging at the exposures 1,500 feet or more nearer sea level farther east in Kansas. It seems evident that the subsidence near Sharon Springs (Wallace County) is due to the formation of a cavity of considerable size in the upper part of the chalk [Niobrara], following which failure of the roof caused the cave-in.

To this thesis Russell[11] objected that the Niobrara is not sufficiently pervious to permit artesian circulation, as indicated by the general failure of wells to find water in it and the absence of issuing springs. He regarded it rather as likely to act as an impervious barrier to the downward movement of ground water. In general, this conclusion seems justified, although locally wells obtain water from the contact

[8] W. D. Johnson, "The High Plains and Their Utilization," *U. S. Geol. Survey Twenty-First Ann. Rept.*, Pt. 4 (1901), pp. 696–725.

[9] *Ibid.*, pp. 705 and 711.

[10] R. C. Moore, *op. cit.*, p. 96.

[11] W. L. Russell, *op. cit.*, p. 607.

of the Hays limestone and Smoky Hill chalk in western Kansas. The relatively brittle chalk and limestone beds of the Niobrara are in many areas cut by faults of small displacement, and the formation is thus presumably pervious to downward circulation at such localities. A fault has been observed that cuts the rocks exposed in the wall of the subsidence near Sharon Springs. Russell's suggestion that the underlying cavern at this place was formed by tension cavities where irregular fault surfaces move past one another has been discussed by Elias,[12] who concluded that, because of the dip of the fault plane, the cave-in is not situated above a possible tension cavity. For this reason and because it seemed to him that if destructuve undermining by ground water were completely excluded there would be no agency that would gradually weaken the roof and cause its sudden collapse, Elias concluded that the subsidence was caused by the formation of a solution cavern in the Niobrara, surface water entering from above and flowing downward chiefly along zones of cracks or breccia along the fault.

A subsidence south of Coolidge, Hamilton County, Kansas,[13] was first attributed to the formation of a solution cavern within the Greenhorn limestone, but the subsequent discovery of croppings of shale identified as the Graneros shale[14] in the walls of the sink led to the conclusion that it might be due to the formation of a cavern by solution of soluble salt beds in the Permian rocks. If the latter hypothesis is true, the cavern has stoped its way upward through the hard Dakota sandstone.

The unusual feature of these recent subsidences is that they occur where limestone is not the surface rock. Sink holes where limestone crops out, or has cropped out, at the surface are of course well known, as are also topographic sinks due to subsequent exposure at the surface by erosion of caverns previously formed by solution in limestones. But most commonly such features are limited geographically by the extent of outcrop of the limestone in which the caverns occur.[15] Increase in the height of the original cavern by failure of the roof has been described,[16] but with implication that the roof finds read-

[12] M. K. Elias, "The Geology of Wallace County, Kansas," *Kansas Geol. Survey Bull. 18* (1931), pp. 230–34.

[13] N. W. Bass, "Recent Subsidence in Hamilton County, Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 2 (February, 1931), p. 204.

[14] K. K. Landes, *op. cit.*, p. 708.

[15] N. M. Fenneman, "Physiography of the St. Louis Area," *Illinois Geol. Survey Bull. 12* (1909), p. 17.

[16] Wallace Lee, "The Geology of the Rolla Quadrangle," *Missouri Bur. Geology and Mines Vol. 12*, 2d Ser. (1914), pp. 65–67.

justment in a natural arch, the readjustment being subsequently disturbed only by continued lateral enlargement of the cavern. Upward extension of caving through sandstone beds overlying cavernous limestones, causing the formation of steep-sided pipes in the partially indurated sandstones, has also been described,[17] the pipes being filled with sandy matrix in which lie blocks of sandstone with their laminae edgewise.

The remarkable natural pipes of the Mons region[18] in Belgium may also have originated in some such way,[19] although several other theories have been proposed to account for them. These great pipes, 100 to 300 feet in diameter, filled with blocks of Cretaceous rocks, extend vertically for distances of more than 800 feet through dipping Carboniferous coal-bearing beds. The pipes have been cut through laterally by the mining of the coal beds, but the bottoms have not been reached.

The formation of solution caverns either in the Greenhorn limestone or in soluble beds in rocks at greater depth, underlying the Dakota sandstone, might have caused the sink-hole features now observed at the Prowers County locality. Either would require the upward propagation of the subsidence through a considerable thickness of overlying beds. Upward propagation of subsidence as a result of mining operations is well known, and experimental studies of subsidence have been made by Callon, Fayol, and others.[20] Fayol's experiments led him to conclude that in stratified deposits the movements are limited by a sort of dome which has for its base the area of removed material, the amplitude of the movements diminishing away from the center of this area. In rocks of considerable strength and rigidity, however, the observed result of removal of material or caving seems to be subsidence in the immediately overlying block where the amplitude of the stresses is greatest and the strength of the rock first exceeded. The collapse of the roof in turn sets up a new system of stresses similar to the preceding one but at a higher level. The result may thus be a natural stoping process forming an upright cylindrical tube which is filled with collapsed material. This tube increases in height until the surface is reached, or until a stratum of

[17] A. H. Purdue and H. D. Miser, *U. S. Geol. Survey Geol. Atlas, Eureka Springs-Harrison Folio* (No. 202) (1916), p. 7.

[18] Henry Briggs, "The Natural Pipes of Mons," *Colliery Engineering*, Vol. 10, No. 110 (1933), pp. 116–18.

[19] George S. Rice, U. S. Bureau of Mines, personal communication.

[20] A compact discussion and a bibliography dealing with subsidence are given by A. M. Bateman in Robert Peele, *Mining Engineers' Handbook*, John Wiley and Sons, Inc., New York (1918), pp. 737–50.

sufficient strength to resist the stresses imposed is encountered, or until equilibrium is attained from some other cause, such as the expansion or swell of the material filling the pipes as compared with its original unbroken volume. The volume of broken rock roughly doubles at surface pressures. The broken filling at depth would initially, of course, increase in volume as much as at the surface, but would not prevent further subsidence until it had been reduced to its stable volume under the prevailing pressure at that depth. Though the swell is much less under high pressures, it is appreciable for pressures such as those obtaining at depths of 1,000 feet. Unless additional material is removed from below, the rising stope therefore should eventually fill with sufficient material to block further subsidence. The effect of subsidence underground at depths of nearly 1,000 feet is, however, known to extend to the surface.

In soft rocks or alluvium the area of subsidence increases upward, whereas in hard rocks the rigidity of the rocks tends to diminish the upward increase of the area of subsidence, so that in rocks of sufficient rigidity it seems possible that the area of subsidence might remain nearly the same as the locus of subsidence moved upward.

Some of the known facts relating to subsidence when considered with the geologic features of the sink holes in Prowers County point to the Greenhorn limestone as the most likely horizon at which the solution caverns were formed, and others point to a lower horizon as more likely. Underlying the Dakota sandstone, which does not exceed 100 feet in thickness, are beds assigned to the Purgatoire formation.[21] These consist of a lower massive sandstone succeeded upward by shales and flaggy sandstones with marine fossils, the formation having a thickness of 120 feet or more. In southwestern Bent and northeastern Las Animas counties, Colorado, the underlying Morrison formation is from 150 to 270 feet thick, extremely variable in lithology but almost everywhere having beds of gypsum at or near the base. In this region, 50 to 75 miles southwest of the Prowers County sink holes, beds of gypsum as much as 17 feet thick are recorded by Duce, who says of the Morrison:

> The determination of its exact thickness is rather difficult because the solution of the gypsum at the base has caused many landslips. . . .

In Hamilton County, Kansas,[22] the formation units below the top of the Dakota are not recognizable in the deep test well of the Wood

[21] J. T. Duce, "Geology of Parts of Las Animas, Otero, and Bent Counties, Colorado," *Colorado Geol. Survey Bull. 27*, Pt. 3 (1924), pp. 84–90.

[22] N. W. Bass, "Geologic Investigations in Western Kansas, Pt. 2, Geology of Hamilton County," *Kansas Geol. Survey Bull. 11* (1926), pp. 74–76.

Oil Company, but the rocks between depths of 105 and 612 feet may contain representatives of the Purgatoire and Morrison. No gypsum is recorded in the well log at the probable base of the Morrison, but some beds of anhydrite and gypsum were encountered in the upper part of the underlying "red beds" of Permian (?) age. Beds of salt aggregating 100 feet in thickness were also recorded in the well log at depths 700 feet and more below the top of the Permian (?). The occurrence of such exceptionally soluble beds as gypsum, anhydrite, and salt, in association with porous sandstones, which are undoubtedly aquifers, offers a highly favorable environment for the formation of solution caverns. However, the stratigraphic horizon at which the subsidence features in Prowers County are now observed is at least 800 feet, and possibly more, vertically above these soluble horizons. Furthermore, the soluble horizons are overlain by some hundreds of feet of competent sandstones, through which it should be difficult for stoping to proceed upward. However, Landes[23] believes that these sandstones may have been penetrated by upward stoping to produce the subsidence south of Coolidge, Hamilton County, Kansas.

Objections may also be urged against the hypothesis that the original cavern or caverns were formed in the Greenhorn limestone. There is some question whether or not the solution of the small actual thickness of limestone beds in that formation could form a sufficiently large cavern to give rise to the features observed. Though the limestone beds of the Greenhorn are conspicuous, only one-fifth of the upper part of the formation is limestone, a still smaller proportion of the basal part is limestone, and the middle part is almost wholly calcareous shale. The total thickness of limestone in the formation probably does not exceed 20 feet. But the exposures at the Prowers County sink holes show clearly that some of the material fell a much greater distance. Unless it can be postulated that some of the material that collapsed into the original cavern was also removed from the bottom by solution, it seems necessary to assume that an approximate equality between the volume of the original cavern and the volume of subsequent subsidence at higher levels was maintained. In order to permit a greater amplitude of subsidence at higher levels, the area of subsidence must have decreased upward. But since the volume of a cylinder increases as the square of the radius but only in direct proportion to its height, the diameter of the horizontal area of one of the original caverns would not need to be much greater than the area of one of the present sink holes in order to permit a consider-

[23] K. K. Landes, *op. cit.*, p. 708.

ably larger amplitude of subsidence. Such an increase of area downward might nevertheless be sufficient to cause coalescence of the observed three sink holes into a single, though irregular-shaped cavern; but whether or not a large single cavern would have permitted subsidence and subsequent upward stoping from several of the weaker points in the roof is unknown. If considerable quantities of soluble material were also removed from the calcareous shales associated with the limestones of the Greenhorn, it would of course make possible a correspondingly greater amplitude of subsidence.

There also appears to be some difficulty in providing a suitable circulation of ground water to effect the hypothetical solution, since the Greenhorn is not an aquifer itself and is embedded between two shale formations. The small fault which now cuts the exposures at the surface may have provided an avenue for circulation, although the relations do not show whether it preceded the sink-hole subsidences or accompanied them. If the fault formed prior to the sinks, it may have permitted downward circulation of water to soluble beds. There are three possible sources of the water, all of which may have contributed. The first is the ground water derived from rainfall upon a somewhat higher level than the present topographic surface. The second is the accumulated ground water which now fills the porous Tertiary beds which cover much of the High Plains and in the past filled the same beds when they extended over the sink-hole locality at a level perhaps 200 feet vertically above the present altitude of the sink holes. Lastly, the Codell sandstone is now an artesian water horizon over much of the Arkansas Valley. In general, the circulation of water in the Codell is probably poor, to judge by the highly variable quality in closely adjacent wells and the fact that the water is strongly saline. At this locality, however, the general structural relations were more favorable to circulation. The sink holes are located on the west flank of a large syncline,[24] where the beds have a regional dip of perhaps 200 feet to the mile. Water moving down dip in the Codell sandstone would encounter the fault, be blocked by the more impervious Carlile shale, and migrate down the fault, to encounter the soluble limestone beds of the Greenhorn. The rocks now exposed at the surface show no evidence of solution, but the presence of vein calcite along the fault shows that there was some circulation of water, though directly indicating, of course, precipitation rather than solution.

Though the hypothesis that the sink holes are developed as a

[24] C. H. Dane and W. G. Pierce, "Geology and Oil and Gas Prospects in Part of Eastern Colorado," *U.S. Dept. Interior Press Mem. 72215* (June 8, 1933).

result of the formation of solution caverns in the Greenhorn limestone or lower soluble horizons appears to be a likely one, it seems that consideration must continue to be given to the possibility of some as yet unexplained process of removal of material from the immediately underlying Carlile shale. Such a process may be presumed to operate near the surface. In this connection it seems desirable to mention that the subsidence described in Hamilton County,[25] Kansas, occurred "near the north rim of a broad, generally basin-shaped valley" and that the Smoky Basin cave-in of Wallace County,[26] as shown in diagrams and description, occurred on higher ground adjoining and not far from the normally dry channel of Smoky Hill River. Though the sink holes in Prowers County occur on a slope into a small creek valley, it seems that the relations there do not afford much support for a hypothesis involving subsurface flow of shales made plastic by water.

The time at which the sink holes in Prowers County were formed can not be closely dated. It obviously occurred before the immediately superjacent topography. Furthermore, since the Smoky Hill marl, which has collapsed into two of the cavities, now is known to crop out no nearer than 2 miles from the site, sufficient time has evidently elapsed to permit its being stripped back by erosion. At the other extreme the collapse probably occurred after the post-Cretaceous folding. Furthermore, it seems that the deformation which occurred at that time under a probable load of thousands of feet of sediments, should not have formed small open faults which would allow the downward percolation of ground water through the Carlile shale, even when the rocks at this level were brought within the zone of circulating ground water by the early Tertiary erosion. In parts of western Kansas and northeastern Colorado, however, the Tertiary beds are themselves irregularly folded and locally broken by small faults. On the whole it seems most likely that the collapse is not earlier than these movements and occurred at some time during the Pleistocene erosion which trenched valleys into the Plains surface.

[25] N. W. Bass, "Recent Subsidence in Hamilton County, Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 2 (1931), p. 202.

[26] M. K. Elias, "The Geology of Wallace County, Kansas," *Kansas Geol. Survey Bull. 18* (1931), pp. 229–31.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 11 (NOVEMBER, 1934), PP. 1506-1536, 4 FIGS.

CORRELATION OF PECAN GAP CHALK IN TEXAS[1]

ALVA C. ELLISOR[2] AND JOHN TEAGLE[3]
Houston, Texas

ABSTRACT

This paper presents the surface mapping of the Pecan Gap chalk from White Cliffs, Arkansas, across northeast Texas to the type locality of the Pecan Gap chalk in Delta County, then southward through Farmersville in Collin County, Rockwall in Rockwall County, Marlin and Lott in Falls County, Rogers in Bell County, Taylor in Williamson County, and into the Anacacho limestone as it occurs west of San Antonio. The Pecan Gap chalk is divided into three paleontological zones, *Flabellammina compressa* zone (basal), *Diploschiza cretacea* zone (middle zone), and *Bolivina incrassata* zone (upper) by means of the microfauna. These faunal zones reveal the fact that the variation in the width of outcrop of the chalk in northeast Texas is due to an unconformity at the base of the chalk across Hunt, Delta, and western Red River counties and to a progressive overlap from Arkansas to Hunt County, where the upper Taylor clays rest unconformably on progressively older beds toward the west. Due to this overlap cutting out the upper chalk zone and the unconformity of the lower zone, the width of outcrop is very narrow in Delta County and western Red River County. The chalk exposed at the type locality at Pecan Gap, Delta County, is equivalent to the lower 50 feet of the chalk at White Cliffs, Arkansas. A subsurface section is given in which the Pecan Gap chalk is shown as a continuous chalk deposited east of the area where on the surface it is apparently missing due to some possible structural features, probably faulting.

INTRODUCTION

Since 1924 it has been the conviction of geologists in the Humble Oil and Refining Company that the chalk exposed in Falls County in the vicinity of Marlin is of the same age as the Pecan Gap chalk, due to the evidence of micropaleontology, and that the Pecan Gap chalk exposed in Hunt, Delta and Red River counties is the equivalent of the lower portion of the chalk at White Cliffs rather than the upper part. A subsurface section made at that time revealed the fact that the Pecan Gap chalk is traceable from northeast Texas to Medina County and that in the vicinity of San Antonio the Pecan Gap chalk rests unconformably on the Austin chalk. It was not until 1933 that any attempt was made by the Humble Company to trace on the surface the Pecan Gap chalk from Hunt into Falls County. In that year, L. W. Stephenson, in a field trip with L. F. McCollum on finding some specimens of *Diploschiza cretacea* Conrad in chalks that Humble geologists had been calling Pecan Gap in the area from Falls to Me-

[1] Read before the Paleontology Division of the Association at the Dallas meeting, March, 23, 1934. Manuscript received, July 21, 1934.

[2] Research geologist for Humble Oil and Refining Company, Houston, Texas.

[3] Geologist for Humble Oil and Refining Company, San Antonio, Texas.

dina County, suggested that they publish their work on the Pecan Gap problem. More than six months of detailed work has been done in the field on this problem and samples were collected from approximately 400 localities for paleontological study.

ACKNOWLEDGMENT

L. F. McCollum was originally one of the collaborators of this paper when the problem was first undertaken. He spent considerable time in the field with the writers covering the entire area mapped and devoted a great deal of attention to the problem, giving every assistance. The writers are greatly indebted to him for his valuable suggestions and coöperation and regret that his resignation from the Humble Oil and Refining Company prevented the fulfilment of the original plan of his collaboration.

The writers are also indebted to J. A. Cushman and Helen Jeanne Plummer for their interest and coöperation in classifying some of the *Foraminifera;* to L. W. Stephenson for his help in the field and for his suggestions and criticisms; to D. C. Matthews of Taylor and Mr. Bell of Waco for their aid in locating data in the field. The writers are indebted to the Humble Oil and Refining Company for their permission to publish this paper and to Fred Carstens and Harold Calhoun for their valuable assistance in the preparation of the manuscript.

HISTORY

In 1887 R. T. Hill[4] described and named the White Cliffs chalk from a bluff on Little River at White Cliffs, Arkansas. But because this name was preëmpted by Powell,[5] Hill[6] changed the name in 1901 to Annona chalk, from the town of that name in Red River County, Texas.

In 1918 L. W. Stephenson[7] described a chalk exposed in a cut of the G. C. & S. F. Railroad ½-mile east of Pecan Gap in Delta County. This was used by him as the type locality of the Pecan Gap chalk, which he later considered a tongue of the Annona. In 1925 the senior writer[8] considered that the chalks at White Cliffs, Clarksville, Pecan Gap, and at the falls of Brazos River near Marlin were all of the same

[4] R. T. Hill, *Arkansas Geol. Survey Ann. Rept. for 1888*, Vol. 2, pp. 87–89.

[5] J. W. Powell, "Geology of Uinta Mountains," *U. S. Geog. and Geol. Survey Terr.* (1876), pp. 41–51.

[6] R. T. Hill, *U. S. Geol. Survey Twenty-First Ann. Rept.*, Pt. 7, p. 341.

[7] L. W. Stephenson, *U. S. Geol. Survey Prof. Paper 120* (1918), p. 156.

[8] Alva C. Ellisor, "The Age and Correlation of the Chalk at White Cliffs, Arkansas, with Notes on the Subsurface Correlations of Northeast Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 9, No. 8 (November, 1925), pp. 1152–64.

age, and suggested that the name Pecan Gap be used for this chalk. In 1928 L. W. Stephenson[9] described two chalks in Falls County, one near Marlin and the other in the vicinity of the town of Lott. These were named the Marlin and Lott chalks, respectively. In 1930 this same trend was continued southwestward by Adkins and Arick,[10] when they described a chalk near Rogers in Bell County and proposed the name Rogers chalk. Also in 1930 W. A. Reiter[11] proposed the name Cooledge chalk for a chalk cropping out on the Marquez salt dome in Leon County and on the Cooledge-Hubbard road, 3 miles northwest of Cooledge, in Limestone County. This chalk is definitely younger than the Pecan Gap chalk, having, however, many species in common.

GENERAL

On studying the Pecan Gap chalk beds in Texas and Arkansas it has become apparent that there is a decided change in the microfauna between the Wolfe City sands and the Pecan Gap chalk. No other similar break in the microfauna occurs above this contact until the basal part of the Nacatoch sands has been reached. So from the point of view of micropaleontology all beds between the Wolfe City sands and the Nacatoch sands fall within one formation.

The lithologic facies of the various chalks described from the Taylor are similar as well as the faunules. On the basis of the microfauna the Pecan Gap chalk can be divided into three faunal zones. It is suggested that these faunal zones, which are based on a detailed study of both the microscopic and the megascopic fossils present, be named the *Flabellammina compressa* zone (basal), the *Diploschiza cretacea* zone (middle), and the *Bolivina incressata* zone (upper). These names are based on characteristic fossils which, although not confined entirely to their individual zones, are nevertheless diagnostic of that faunal association. Combined, these zones make a fairly uniform lithologic unit which, as shown on the map (Fig. 1), can be traced from White Cliffs, Arkansas, to Medina County, Texas.

NAME

One can readily see from the history that the question of a name for these chalk beds is a difficult one. As Thomas and Rice[12] pointed

[9] L. W. Stephenson, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12, No. 1 (January, 1928), pp. 52–55.

[10] W. S. Adkins and M. B. Arick, "Geology of Bell County, Texas," *Univ. of Texas Bull. 3016* (1930).

[11] W. A. Reiter, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 3 (March, 1930), pp. 322–23.

[12] Norman L. Thomas and Oliver W. Rice, "Notes on the Annona Chalk," *Jour. of Paleont.*, Vol. 6, No. 4 (December, 1932), p. 319.

out, the chalk in question may be considered as having two names and three type localities, namely, White Cliffs, Annona, and Pecan Gap. It is unfortunate that Hill's original name of White Cliffs is preoccupied, as the most complete section of the chalk occurs at this locality. The name Annona, oldest in point of priority, is unsuited because of the fact that the chalk does not occur there at all, but at White Rock and Clarksville, several miles farther north and northwest. The name Pecan Gap, first used by Stephenson for the outcrops in Delta, Hunt, and Collins counties, was suggested by Alva C. Ellisor[13] in 1925 as the name for these chalk beds when she correlated the chalks occurring at Pecan Gap, Clarksville, White Rock, and White Cliffs. Since then the name Pecan Gap has come to be used for these chalk beds by geologists generally, has become firmly established in the oil industry as a horizon marker, and has been accepted in other geologic fields. Therefore, the writers believe that Pecan Gap is the most acceptable name, and have so used it in the present work.

EXPOSURES AT WHITE CLIFFS

The Chalk bluff on Little River at White Cliffs, Arkansas (localities 1 and 2 on Figure 1), was first described by Hill and later by Taff and is the original type locality of the Pecan Gap chalk of this paper. This locality still presents a more complete section of the chalk than any other single locality and as such deserves special consideration.

Taff[14] described the exposure of chalk on the Little River at White Cliffs as follows.

	Feet
1. Massive, creamy-white chalk, in beds from 1 to 10 feet thick separated by thin partings of very slightly laminated chalk	60
2. Massive, dull bluish-white siliceous chalk, slightly harder than the pure chalk of No. 1. This chalk is practically without indication of bedding, and because of its hardness it projects in a steep bench overhanging the less chalky and friable beds below	25
3. Massive, very siliceous, dull blue argillaceous chalk marl. This bed contains more than twice as much sand and three times as much clay, as the overlapping bed. The rock is very friable and weathers in recesses beneath the siliceous chalk	8
4. Bluish, sandy, chalky marl, containing great numbers of fossil shell *Gryphaea vesicularis* var. Except for the abundant fossils, this rock would be classed with No. 3, though it is probably slightly more sandy	7
5. Bluish sandy marl, gradually increasing in sandiness from the top downward to the level of the river. This bed contains *Gryphaea vesicularis* var., but not in such abundance as No. 4; also many fossils of the large and heavy oyster *Exogyra ponderosa*, as well as others common to the upper Cretaceous marls	35
Total Thickness	135

[13] Alva C. Ellisor, "The Age and Correlation of the Chalk at White Cliffs, Arkansas, with Notes on the Subsurface Correlation of Northwest Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 9, No. 8 (November, 1925).

[14] J. A. Taff, *Twenty-Second Ann. Rept., U. S. Geol. Survey*, Pt. 3 (1902), pp. 706–07.

In a study of the fauna, both at this locality and at the quarry a little northeast of the bluff, it is found that the upper two faunal zones are present and that the basal or *Flabellammina compressa* zone is either absent or not exposed in the bluff at the time the writers collected samples. The *Bolivina incrassata* zone is included in the uppermost 60 feet of Taff's section No. 1. The balance of his section is included in the *Diploschiza cretacea* zone. The list of species occurring in the *Bolivina incrassata* zone is given in column No. 1 of the check list.

In samples collected at the base of Taff's second division No. 2, or 85 feet below the top of the bluff, a few fragments of *Diploschiza cretacea* Conrad (the type fossil of this zone) were found, also *Terebratulina* cf. *filosa* Conrad and a microfauna typical of the *Diploschiza cretacea* zone as shown by the species in the faunal check list, column No. 2. Beds Nos. 3, 4, and 5 of Taff's section have typical Pecan Gap fauna, the last actual sample being collected 5 feet above the base of his No. 5, or 130 feet below the top of the bluff. Column No. 3 of the check list gives a list of species occurring in the *Gryphaea vesicularis* bed or Taff's division No. 4.

The writers have found that the *Gryphaea vesicularis* var., mentioned by Taff in division No. 4, forms a definite horizon in the lower part of the *Diploschiza cretacea* zone which is quite persistent and is mappable for considerable distance in some areas. This horizon has been traced across Red River and Delta counties and is present in the railroad cut 0.5 mile east of Pecan Gap in Delta County which Stephenson has described as the type locality of his Pecan Gap chalk. For this reason and also because the microfauna at Pecan Gap is the same as in Taff's divisions Nos. 4 and 5 at White Cliffs, the chalk at Pecan Gap is correlated with this portion of the bluff.

The chalks near Marlin, Lott, and Rogers, which have an abundance of *Diploschiza cretacea* Conrad, and *Terebratulina* cf. *filosa* Conrad, contain the same microfauna as is found in the lower portion of Taff's division No. 2 of the White Cliffs section. The chalks at Marlin, Lott, and Rogers and the chalk at Pecan Gap are in the *Diploschiza cretacea* zone, but the chalk cropping out at Pecan Gap is in the lower portion of the *Diploschiza cretacea* zone.

FLABELLAMMINA COMPRESSA ZONE

The *Flabellammina compressa* zone which takes its name from the fossil *Flabellammina compressa* (Beissel) occurs in the basal portion of the Pecan Gap chalk. The type locality of this zone is on the Forney-Mesquite road 0.7 miles west of Forney in Kaufman County

(locality 24 on Figure 1). The beds here are composed of a soft chalky marl, gray or tan in color and weathering to a neutral brownish white. *Flabellammina compressa* (Beissel) was first noted at this locality by Alexander and Smith.[15] In addition to this one the zone includes the following *Foraminifera*.

Anomalina complanata Reuss
Anomalina involuta (Reuss)
Anomalina rubiginosa Cushman
Astacolus taylorensis Plummer
Bolivinoides decorata Jones var. *delicatula* Cushman
Buliminella carseyae Plummer
Cibicides excolata (Cushman)
Clavulina clavata Cushman
Clavulina trilatera Cushman
Dentalina aculeata d'Orbigny
Dentalina soluta Reuss
Eouvigerina gracilis Cushman
Flabellina interpunctata von der Marck
Globigerina cretacea d'Orbigny
Globigerinella asper (Ehrenberg)
Globotruncana arca (Cushman)
Globotruncana canaliculata (Reuss)
Globotruncana canaliculata (Reuss) var. *ventricosa* White
Globotruncana fornicata Plummer
Globorotalia micheliniana (d'Orbigny)
Globulina lacrima Reuss
Gumbelina globulosa (Ehrenberg)
Gumbelina striata (Ehrenberg)
Gumbelina tessera (Ehrenberg)
Gyroidina umbilicata (d'Orbigny)
Heterostomella faveolata (Marsson)
Lagena acuticosta Reuss
Lenticulina rotulata Lamarck
Marginulina intermedia (Philippi)
Marssonella oxycona (Reuss)
Nodosaria affinis Reuss
Planulina taylorensis (Carsey)
Pseudouvigerina plummerae Cushman
Pullenia quinqueloba (Reuss)
Saracenaria italica De France
Spiroplectammina anceps (Reuss)
Spiroplectoides rosula (Ehrenberg)
Textularia ripleyensis W. Berry
Valvulineria cf. *umbilicatula* (d'Orbigny)
Ventilabrella carseyae Plummer
Bolivinita eleyi Cushman
Bolivinita planata Cushman
Clavulina insignis Plummer
Dentalina annulata (Reuss)
Dentalina cf. *consobrina* d'Orbigny
Dentalina legumen (Reuss)
Frondicularia golfussi Reuss
Frondicularia verneuliana d'Orbigny
Frondicularia gracilis Franke
Hemicristellaria ensis (Reuss)

[15] C. I. Alexander and J. P. Smith, "Foraminifera of the Genera Flabellammina and Frankeina from the Cretaceous of Texas," *Jour. of Paleont.*, Vol. 6, No. 4 (December, 1932), pp. 299–311.

Nodosaria intercostata Reuss
Pulvinulinella alata (Marsson)
Flabellammina compressa (Beissel)
Frankeina cushmani Alexander & Smith
Gaudryina bentonensis (Carmon)
Nodosaria obscura Reuss
Clavulina compressa Cushman
Kyphopyxa christneri (Carsey)
Loxostoma clavata (Cushman)
Nonionella cretacea Cushman
Gaudryinella capitosa Cushman

The *Flabellammina compressa* zone is present at many other localities besides the one in Kaufman County previously described. A few of the more important localities are described.

Red River County.—The town of White Rock in Red River County, Locality 8 on Figure 1, is built on a massive hard bluish white sandy chalk which, according to its fauna, should be included in this zone. The outcrop here is very extensive and is exposed in flat ledges having very little indication of bedding. These ledges extend northward and westward from the townsite for a distance of somewhat more than a mile before the base of the formation is reached. Other localities in Red River County are in a small creek in the north part of the town of Clarksville, also in the southwest part of Clarksville several blocks south of the Paris Highway, on a road at a point 0.7 mile southwest of McCoy and 2 miles southeast of Fulbright.

Collin County.—The *Flabellammina compressa* zone is represented in this county by two major localities. One, located on a road 1.8 miles east of Copeville, is soft, blue and white chalky marl containing some sand; the other, outcropping in a deep ditch 3.4 miles south of Farmersville and 2 miles east of the G.C. & S.F. Railroad, is soft, bluish gray, friable sandy marl containing some bentonite.

Rockwall County.—In this county the *Flabellammina compressa* zone is well defined and extends as a north-south band from the Collin County line on the north to the Kaufman County line on the south. The band varies in width from 1.5 to 2 miles and includes most of what previously has been mapped as Pecan Gap by Stephenson and others.[16]

Good exposures can be seen on the Greenville-Dallas Highway in the scarp 0.5 mile west of Rockwall County courthouse, and at a point 1.7 miles east of Rockwall in the ditch on the north side of the road. The chalk here is fairly hard, slightly sandy, blue-gray in color, and shows some tendency to have conchoidal fracture. Good exposures may also be seen along the road from Rockwall to Heath at several

[16] C. H. Dane and L. W. Stephenson, "Notes on Taylor and Navarro Formations," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12, No. 1 (January, 1928), pp. 42–44.

points. The chalk here is massive, but not particularly hard, bluish gray on fresh exposure, but weathering to brownish white, slightly sandy and locally bentonitic. In addition to these there are some good exposures at several isolated localities; notably on Buffalo Creek 3.5 miles south of Rockwall, and in a small creek 0.5 mile south of the Collin County line on the road to Millwood. The rock here is medium-bedded, friable bluish gray sandy chalk grading in some places to chalky marl. A few thin beds of very sandy material are present in these localities which weather as flaggy sandstone.

Kaufman County.—The band in which the *Flabellammina compressa* zone is exposed is not as definite here as in Rockwall County on the north. Nevertheless there are numerous exposures of this zone in the county and they fall roughly into two groups. Those exposures on the extreme western edge of the Pecan Gap outcrop, of which the type locality near Forney is one, constitute the basal portion of the zone; and those exposures immediately east of this line constitute the upper portion of the zone.

The basal portion of the zone is exposed in addition to the locality at Forney, in Mustang Creek approximately 2.5 miles northwest of Crandall, and in the fields on the northeast side of Mustang Creek at a point 4 miles south of Forney. The rock is massive, fairly soft, blue to white, and contains a good deal of sand in the matrix. Very few large fossils were noted, but the rock contained an abundance of *Foraminifera.* The upper portion of the zone is exposed along the sides of secondary roads in the Juan Lopez Survey approximately 3.5 miles north of Forney and on a secondary road in the southern portion of the Absolom Hyer Survey 2.5 miles southeast of Forney. Here the formation is a soft chalky, brownish white marl, containing much clay as well as some sand, though not as much as the basal portion of the zone.

Navarro County.—The *Flabellammina compressa* zone is not exposed south of Kaufman County except for a few scattered exposures at isolated localities in Navarro County. Along the right of way of the T. & B. V. Railroad at a point 3.6 miles northwest of Emhouse (locality 27 in Figure 1), and in a tank along the Barry-Cryer Creek road 1.2 miles north of Barry, are exposures of a soft, brownish white chalky marl which have the fauna of the *Flabellammina compressa* zone. An exposure of bluish gray sandy marl on a branch of Cottonwood Creek 2.8 miles south of Barry contains a similar fauna. A mile south of this point (locality 29 in Figure 1), along a secondary road, a series of deep gulches afford excellent exposures of this zone in the lower portion of their walls. The facies here is a soft, buff-colored,

sandy marl containing several specimens of the oyster *Exogyra ponderosa* and numerous other shell fragments. The *Bolivina incrassata* zone is present in the upper portion of the walls of the gulches and here appears to rest conformably on the *Flabellammina compressa* zone. There is no break whatever in the lithologic character of the beds, and the *Diploschiza cretacea* zone is absent at this point, although present elsewhere in the county.

DIPLOSCHIZA CRETACEA ZONE

The middle or *Diploschiza cretacea* zone which takes its name from the fossil *Diploschiza cretacea* Conrad is the most important of the three zones of the Pecan Gap chalk, since it is present in the major portion of the outcrop, while neither the *Flabellammina compressa* zone nor the *Bolivina incrassata* zone extends farther southwestward than Navarro County. The type locality of the *Diploschiza cretacea* zone is in a ditch on a secondary road 3.5 miles north of Marlin and 1.1 miles east of Harmony Hill in Falls County (locality 33 in Figure 1). The beds here are composed of soft, thin-bedded, argillaceous white chalk. The rock is very friable and contains numerous fossil fragments of *Inoceramus* sp., *Exogyra ponderosa*, *Diploschiza cretacea*, and *Terebratulina* cf. *filosa* as well as abundant *Foraminifera*. A list of the *Foraminifera* of this zone is as follows.

Anomalina complanata Reuss
Anomalina involuta (Reuss)
Anomalina rubiginosa Cushman
Anomalina pertusa (Marsson)
Arenobulimina presli (Reuss)
Astacolus taylorensis Plummer
Bolivinoides decorata Jones var. *delicatula* Cushman
Buliminella carseyae Plummer
Cibicides excolata (Cushman)
Clavulina clavata Cushman
Clavulina trilatera Cushman
Dentalina aculeata d'Orbigny
Dentalina megapolitana Reuss
Dentalina soluta Reuss
Dorothia bulletta (Carsey)
Eouvigerina gracilis Cushman
Flabellina interpunctata von der Marck
Flabellina projecta (Carsey)
Globigerina cretacea d'Orbigny
Globigerinella asper (Ehrenberg)
Globotruncana arca (Cushman)
Globotruncana canaliculata (Reuss)
Globotruncana canaliculata (Reuss) var. *ventricosa* White
Globotruncana fornicata Plummer
Globorotalia micheliniana (d'Orbigny)
Globulina lacrima Reuss
Gumbelina globulosa (Ehrenberg)
Gumbelina striata (Ehrenberg)
Gumbelina tessera (Ehrenberg)
Gyroidina umbilicata (d'Orbigny)

Heterostomella faveolata (Marsson)
Heterostomella stephensoni (Cushman)
Lagena acuticosta Reuss
Lenticulina rotulata Lamarck
Marginulina intermedia (Philippi)
Marssonella ellisorae Cushman ms. sp.
Marssonella oxycona (Reuss)
Planulina taylorensis (Carsey)
Pseudouvigerina plummerae Cushman
Pullenia quinqueloba (Reuss)
Spiroplectammina anceps (Reuss)
Nodosaria affinis Reuss
Saracenaria italica De France
Spiroplectoides rosula (Ehrenberg)
Textularia ripleyensis W. Berry
Valvulineria cf. *umbilicatula* (d'Orbigny)
Ventilabrella carseyae Plummer
Bolivinita eleyi Cushman
Bulimina minuta (Marsson)
Bulimina trochoides (Reuss)
Cibicides involuta (Reuss)
Cibicides wuellerstorfi (Schwager)
Clavulina insignis Plummer
Cornuspira cretacea Reuss
Dentalina annulata (Reuss)
Dentalina cf. *consobrina* d'Orbigny
Dentalina legumen (Reuss)
Dorothia stephensoni Cushman ms. sp.
Frondicularia archiciana d'Orbigny var. *strigillata* Bagg
Frondicularia golfussi Reuss
Frondicularia lanceola Reuss
Frondicularia verneuliana d'Orbigny
Frondicularia gracilis Franke
Hemicristellaria ensis (Reuss)
Lituola taylorensis Cushman & Waters
Marginulina bullata Reuss
Marginulina elongata d'Orbigny
Nodosaria intercostata Reuss
Nodosaria radicula (Linne)
Pleurostomella subnodosa Reuss
Pyrulina cylindroides (Roemer)
Ramulina globulifera H. B. Brady
Robulus megalopolitana (Reuss)
Robulus munsteri (Reuss)
Valvulineria allomorphinoides (Reuss)
Flabellammina compressa (Beissel)
Frondicularia archiciana d'Orbigny
Frondicularia verneuliana d'Orbigny var. *bidentata* Cushman
Lingulina furcillata Berthelin
Nodosaria obscura Reuss
Textularia sp. A
Tritaxia ellisorae Cushman ms. sp.
Clavulina compressa Cushman
Clavulina disjuncta Cushman
Flabellina rugosa d'Orbigny
Globulina lacrima Reuss var. *horrida* Reuss
Kyphopyxa christneri (Carsey)
Gyroidina depressa (Alth)
Haplophragmoides rugosa Cushman & Waters
Loxostoma clavata (Cushman)

The lower 75 feet of the Bluff at White Cliffs, Arkansas, contains the fauna of this zone. The same zone can be traced without much

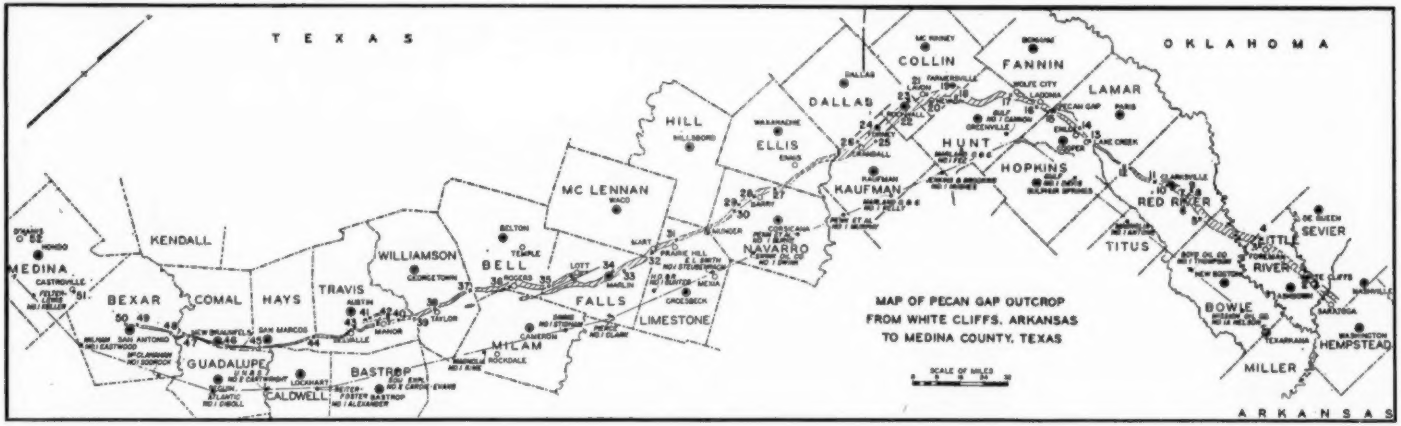


Fig. 1

LOCALITIES POSTED ON MAP

1 and 2—White Cliffs, Ark. 3 and 4—Section near Rocky Comfort, Ark. 5—Under culvert at Henrietta School 1 mile west of Henrietta Church, Red River Co., Tex. 6—Lawson Creek about a mile south of Clarksville-Texarkana Highway, Red River Co., Tex. 7—Lawson Creek at crossing of Clarksville-Texarkana Highway. 8—White Rock, Red River Co. 9—About a mile north of White Rock. 10—Southwest part of Clarksville a few blocks south of Paris Highway. 11—0.7 mile southwest of McCoy, Red River Co. 12—1.5 miles west of Deport, Red River Co. 13—Lake Creek Quarry 1 mile north of Lake Creek, Delta Co. 14—Quarry at Mount Joy north of Enloe. 15—0.5 mile east of Pecan Gap in G.C. & S.F.R.R. cut. 16—In bed of small creek at crossing of highway 2 miles south of Ladonia in Fannin Co. 17—Five miles south of Wolfe City in pit just west of Highway 34. 18—In creek 0.3 mile east of Hunt-Collin Co. line and 1.5 miles south of M.K. & T.R.R. 19—In G.C. & S.F.R.R. cut at north edge of Farmersville, Collin Co. 20—In deep wash on east-west road 1.3 miles south of Nevada, Collin Co. 21—2.7 miles south of Copeville, Collin Co., on Highway 78. 22—On road 0.7 mile east of Union School. 23—In wash at side of road 4.7 miles north of Rockwall. 24—0.7 west of Forney on Forney-Mesquite road, Kaufman Co. 25—In Creek 4 miles southeast of Forney. 26—In Mustang Creek approximately 2.5 miles northwest of Crandall. 27—In cut of T. & B.V.R.R. 3.6 miles northwest of Emhouse. 28—On road 1.7 miles south of Barry. 29—In branch of Cottonwood Creek 2 miles northeast of Dresden. 30—On road 2.7 miles northwest of Silver City and 1.7 miles east-southeast of Dresden, Navarro Co. 31—In tank on Dyer tract, P. Conlee Survey, 2 miles northwest of Prairie Hill, Limestone Co. 32—In Big Creek at crossing of Mart-Riesel Highway 1 mile southwest of Mart. 33—In draw 1 mile east of Harmony Hill, Falls Co. 34—On northwest edge of Marlin. 35—On road 2 miles southeast of Westphalia, Falls Co. 36—In creek 1.6 miles south of Rogers. 37—In field south of public road 2.5 miles east-southeast of Bartlett, Williamson Co. 38—One mile west of city limits of Taylor, Williamson Co., in old brick pit on old Highway 43. 39—On Brushy Creek 1.7 miles northwest of Rice's Crossing. 40—Wilbarger Creek where it crosses road 1.4 miles south-southwest of Richland Schools. 41—In cut on Austin-Manor Highway just east of Walnut Creek. 42—1.5 miles southwest of Manor. 43—Bluff on Colorado River 1 mile north of Del Valle just below Hornsby's Bend. 44—In bed of small creek 0.5 mile south of Hayes-Travis Co. line and 3 miles south of Creedmoor. 45—Four miles south of San Marcos on road to Seguin. 46—Near New Braunfels on New San Antonio-New Braunfels Highway. 47—On Highway 2, 0.2 mile southwest of Comal Co. line in Guadalupe Co. 48—On Highway 2, 1.5 mile northeast of Judson road in Bexar Co. 49—In Longhorn Cement Quarry, Republic Cement Company, Bexar Co. 50—Quarry at Cementville, northwestern edge of San Antonio. 51—In bank of Medina River at Castroville. 52—In Seco Creek approximately 3 miles north of D'Hanis.

difficulty through most of the Texas outcrop of the Pecan Gap formation and directly into the upper portion of the Anacacho limestone in Medina County. It would be impossible to describe in detail all of the exposures of the *Diploschiza cretacea* zone in a paper of this length, but a discussion of some of the more important localities has been attempted.

Red River County.—An extremely good section of the *Diploschiza cretacea* zone can be seen in Lawson Creek beginning at a point on the road 1.3 miles south of the town of White Rock and continuing south down the creek for a distance of nearly 2 miles. The rock is exposed continuously in the greater part of this distance and, except for small local variations in hardness, is uniformly composed of medium-bedded white and bluish white slightly sandy chalk. Collections of *Diploschiza cretacea* were made by Stephenson and the writers at several points along the creek. At the crossing of the Clarksville-Texarkana Highway at a point approximately 7 miles east of Clarksville (locality 7 in Figure 1), a good specimen of *Echinocorys texana* was found as well as numerous fragments of *Diploschiza cretacea*, *Inoceramus* sp., and *Terebratulina* cf. *filosa*. This zone is also exposed 1 mile south of Clarksville on a road leading from the eastern side of the town. Here the rock is a hard, thin-bedded, bluish white sandy chalk.

Delta County.—A good exposure of the basal part of this zone can be seen in a quarry 0.3 mile north of Mount Joy (locality 14 in Figure 1). The rock here is a hard, massive, bluish white sandy chalk containing numerous *Gryphaea vesicularis*, *Pecten* sp., and some *Inoceramus* fragments. This exposure, together with the one 0.5 mile east of Pecan Gap in a cut of the G.C. & S.F. Railroad (locality 15 in Figure 1), is included in the *Gryphaea vesicularis* horizon of the lower part of the *Diploschiza cretacea* zone.

This exposure at Pecan Gap is the type locality of the Pecan Gap chalk.[17] Here is exposed a hard, thin-bedded, bluish white, sandy chalk which is fossiliferous. In the east end of the cut an unconformity between the chalk and the underlying Wolfe City sand is clearly seen. The unconformity is marked by phosphate nodules and a thin pebble conglomerate at the base of the chalk. A road parallels the railroad at this point; and on the other side of it, south of the railroad, a recent quarry affords an excellent exposure of the chalk. *Gryphaea vesicularis* was noted in the quarry.

Fannin County.—One mile south of Ladonia on an old road is an outcrop of thin-bedded, friable bluish white sandy chalk which is

[17] L. W. Stephenson, "A Contribution to the Geology of Northeastern Texas and Southern Oklahoma," *U.S. Geol. Survey Prof. Paper 120* (1918), pp. 154–56.

exposed in flat ledges. This chalk contains the fauna of the *Diploschiza cretacea* zone including the *Gryphaea vesicularis*. The *Bolivina incrassata* zone occurs 2 miles south of Ladonia.

Hunt County.—All of the chalk exposures found in this county, with the exception of one locality of the *Bolivina incrassata* zone near the Collins County line, are included in the *Diploschiza cretacea* zone. Two localities deserve special mention. One, in a shallow pit or quarry 5 miles south of Wolfe City on the Greenville-Wolfe City road (locality 17 in Figure 1) is thin-bedded, friable, bluish white sandy chalk and contains the microfauna of the *Gryphaea vesicularis* horizon. The other, in and around the town of White Rock (not to be confused with White Rock in Red River County) is bluish white, hard friable sandy chalk which occurs in flat ledges. North of the town tanks have been dug in the chalk for water reservoirs and there are several good exposures.

Collin County.—In Collin County as in Rockwall, the *Bolivina incrassata* and *Flabellammina compressa* zones are well developed and occupy broad outcrops. Only one locality of the typical fauna of the *Diploschiza cretacea* zone was found. The fauna in the area that should contain the typical species of the *Diploschiza cretacea* zone has become very scant and the formation is marl or marly clay. At one locality in a small creek 0.7 mile southeast of Farmersville, the lithologic appearance is that of grayish white soft sandstone. The "sand grains" proved to be an abundance of *Globotruncana* and *Globigerina*. The locality (No. 21 in Figure 1) which contains a typical Pecan Gap microfauna of the *Diploschiza cretacea* zone is on the Farmersville highway between Lavon and Copeville 2 miles south of Copeville. The outcrop here is a thin-bedded gray sandy chalky marl.

The one unusual circumstance concerning this last locality is that it lies appreciably farther west than any other locality of Pecan Gap in this area. L. W. Stephenson[18] called attention to an outcrop of chalky marl along this same general trend in a creek approximately 0.5 mile south of Lavon, but samples collected at this point showed a microfauna of Taylor age somewhat older than Pecan Gap.

Navarro County.—With the exception of one isolated locality in Navarro County, typical *Foraminifera* of the *Diploschiza cretacea* zone are apparently absent from Collin County southward to Limestone County. However, from Limestone County southward, the zone crops out continuously to Medina County. The single locality in Navarro County (No. 30 in Figure 1) is located on a secondary

[18] L. W. Stephenson, "Unconformities in Upper Cretaceous Series of Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 10 (October, 1929), p. 1331.

road 2.7 miles northwest of Silver City and 1.7 miles east-southeast of Dresden. The chalk is exposed in the ditch on the north side of the road and is composed of soft, white, argillaceous chalk which weathers very easily. Comparatively few species of *Foraminifera* were found, but all were diagnostic of this zone.

Limestone County.—Beginning in this county at a point near Delia and continuing southward to Rogers the outcrop of the Pecan Gap chalk had already been mapped by L. W. Stephenson. As has been pointed out, this chalk includes the Marlin, Lott, and Rogers chalks. From this point southward to Medina County the Pecan Gap chalk can be mapped into the Anacacho limestone.

All exposures are included within the limits of the *Diploschiza cretacea* zone. In this county several good exposures can be found between Delia and Mart in McLennan County. One, located on a secondary road 0.8 mile west-southwest of Delia, is composed of soft, white-to-cream-colored, argillaceous chalk. Another (locality 31 in Figure 1) is in a tank on the Dyer tract, P. Conlee Survey, approximately 2 miles northwest of Prairie Hill. Here the rock is massive, medium-bedded white chalk, fairly soft on fresh exposure but becoming hard after weathering. *Diploschiza cretacea* and *Terebratulina* cf. *filosa* were both collected from this locality. Farther south the chalk is exposed in a tank on the Waco-Cooledge Highway 2.2 miles east of Watt, but is much weathered. A third exposure of soft, white-to-cream-colored, slightly sandy chalk lies on the Limestone-McLennan County line in the John Nelson Survey approximately 1.5 mile north of Mart.

On the Cooledge-Hubbard road 0.6 miles southeast of Munger, is a chalk outcrop which the writers believe is the same locality that was mentioned by Reiter[19] as the type locality of his Cooledge chalk. Samples of this chalk were collected and the fauna was found to be slightly younger in age than the fauna of the Pecan Gap chalk.

McLennan County.—The Pecan Gap chalk crosses the extreme southeastern edge of McLennan County between Limestone and Falls counties. One mile southwest of Mart, where the Mart-Riesel Highway crosses Big Creek, is an exceptionally good exposure of the chalk (locality 32 in Figure 1). The rock here is thin-bedded, slightly sandy, medium hard chalk, white-to-cream-colored at the top and grading into grayish blue at the base. Some very large specimens of *Diploschiza cretacea* were found, as well as numerous other shell fragments.

[19] W. A. Reiter, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 3 (March, 1930), pp. 322–23.

Falls County.—The type locality of the *Diploschiza cretacea* zone, which occurs in this county, has already been described. The chalk forms a more or less continuous band across the county and is cut by a fault in the vicinity of Lott. Because of this it was originally believed that there were two chalk beds in the county, the Marlin chalk on the north, and the Lott chalk on the south. However, the fact that these two chalks are one and the same is now well known. The chalk outcrop has a more or less uniform width of 1.5–2 miles. In that outcrop *Diploschiza cretacea* is found near the top of the chalk and *Gryphaea vesicularis* toward the base.

In this county the facies is primarily a medium-bedded white-to-bluish gray, slightly argillaceous and in places slightly sandy chalk. The hardness of the rock varies locally and in some places the chalk becomes a little marly, but in general stands up as a resistant rock. Besides the type locality, good exposures of the chalk can be seen in the extreme north portion of the town of Marlin and along a graveled road toward the north for a distance of about 2 miles, in the falls of the Brazos River 4 miles south of Marlin, in a small creek 4.4 miles east of Lott and 3 miles west of Cedar Springs, and in a ditch along a local road 2 miles east of Westphalia.

Bell County.—The Pecan Gap chalk crosses the eastern corner of this county in an outcrop approximately 2 miles wide and includes the Rogers chalk as it was described by Adkins and Arick.[20] The beds here are a hard, usually massive, medium-bedded white chalk and contain among other fossils, *Diploschiza cretacea*, *Inoceramus* sp., and *Terebratulina* cf. *filosa*. Good exposures can be seen in Cyclone Branch at the town of Cyclone, along a road 1 mile north of Gindale, in a small creek 2.3 miles northwest of Gindale, and in a small creek 1.5 miles southwest of Rogers (locality 36 in Figure 1). This last is the type locality of the Rogers chalk.

Williamson County.—Exposures of the chalk are not as prominent in this county as in some of the others. However, several good localities were noted and fossil collections made. In a field south of the public road 2.5 miles east-southeast of Bartlett is an exposure of fairly hard white chalk containing *Diploschiza cretacea*, *Terebratulina* cf. *filosa*, and a microfauna characteristic of the *Diploschiza cretacea* zone. A particularly good exposure was noted 1 mile west of the city limits of Taylor on old Highway 43 in an old brick pit (locality 38 in Figure 1). The chalk here is massive, white-to-cream-colored, medium hard, slightly argillaceous. Numerous specimens of *Diplos-*

[20] W. S. Adkins and M. B. Arick, "The Geology of Bell County," *University of Texas Bull. 3016* (1930), pp. 65–66.

chiza cretacea and *Terebratulina* cf. *filosa* were collected as well as some *Echinoid* spines and *Inoceramus* prisms. The fauna here belongs at the top of the *Diploschiza cretacea* zone, and is very slightly younger than the chalk in Falls County. Another well known locality (number 39 in Figure 1) is on Brushy Creek near Rice's Crossing. Three separate exposures are present in the bank of the creek; one 0.7 mile northwest of the Crossing, one 1.7 mile northwest of the Crossing, and one 2 miles northwest of the Crossing. All are composed of a medium-bedded, slightly sandy, slightly argillaceous, friable chalk. The color grades from white or cream-colored at the top to bluish gray near the water's edge. Numerous specimens of *Diploschiza cretacea, Terebratulina* cf. *filosa,* and fragments of *Inoceramus* sp. were found. This locality, like the one at Taylor, should be included in the very top of the *Diploschiza cretacea* zone.

Travis County.—The Pecan Gap chalk crosses this county in a southwesterly direction, and is represented by numerous exposures throughout the county. One (locality 40 in Figure 1) in Wilbarger Creek where it crosses the road 1.4 mile south-southwest of Richland School, is massive, heavy-bedded, hard white chalk. It is exposed for a distance along the creek and is fossiliferous. Another is in a deep wash 1.5 miles north of Manor. The beds here are of soft, brownish white, chalky marl and not very fossiliferous. However, the few species which were found belong in the *Diploschiza cretacea* zone. An exposure of soft cream-white chalk occurs in a small creek 4 miles south-southwest of Manor. The rock here has numerous shells of the oyster *Exogyra ponderosa* as well as some *Gryphaea vesicularis.*

About 4 miles west of this line of outcrops is a very good exposure of the Pecan Gap chalk in a cut on the Austin-Manor highway just east of Walnut Creek (locality 41 in Figure 1). This exposure is soft white chalky marl and contains fossils of *Diploschiza cretacea, Terebratulina* cf. *filosa,* and others. There are no other exposures near here and the chalk is considerably out of line with respect to the general trend of the chalk outcrops.

In the bank of Colorado River, at the bottom of what is known as Hornsby's Bend and located 1 mile north of Del Valle is an extensive exposure of the chalk together with some of the underlying Taylor marl. The chalk itself is massive, grayish white in color, and hard. It is fossiliferous and belongs to the lower part of the *Diploschiza cretacea* zone. South of Colorado River the base of the Pecan Gap chalk and the top of the Austin chalk are noticeably close together. Farther southwest, they rest directly one on the other as will be shown. Across the balance of this county, however, the two remain separate and the

Pecan Gap extends from the river southwestward to the vicinity of Creedmoor. Exposures occur in Sneeds Branch, just south of Colorado River, in a small creek 5 miles south of Del Valle, and on the old Austin-Lockhart road 2 miles north of Creedmoor at the community of Carl. In all of these localities the rock exposed is medium hard, fairly massive, white-to-cream-colored chalk.

Hayes and Comal counties.—Due to the very great faulting along the Balcones fault zone, it is somewhat difficult to map in accurate detail the outcrop of the Pecan Gap through these two counties. However, exposures were observed at several places and collections of the fossils present were made. An exposure of soft, white-to-cream-colored chalky marl was observed in a small creek 0.5 mile south of the Hays-Travis county line and 3 miles south of Creedmoor (locality 44 in Figure 1). Four miles south of San Marcos on the road to Seguin (locality 45 in Figure 1) is an exposure of soft white argillaceous chalk having an abundance of *Gryphaea vesicularis* and is part of the *Gryphaea vesicularis* horizon in the lower portion of the *Diploschiza cretacea* zone.

Near New Braunfels the complete Austin chalk section has been faulted out in places, and only a portion of the Pecan Gap is exposed. Good exposures occur at numerous points along the new highway between San Antonio and New Braunfels. Here the rock is predominantly soft white, slightly argillaceous chalk.

Bexar County.—Southwest of the Comal-Guadalupe county line, the Pecan Gap chalk is exposed along the old San Antonio-New Braunfels Highway, the best exposures being on the points of high topography. In Cibolo Creek near Selma the Austin chalk is well exposed, and is overlain on the surrounding hills by Pecan Gap chalk. This is the first point noted in the field where the two formations appear to be in contact with each other, although in the wells in Guadalupe County the Pecan Gap rests unconformably on the Austin. At the Longhorn Cement Pit (locality 49 in Figure 1), lying somewhat southwest of this creek and located on a branch of the M.K. & T. Railroad near Fratt, the uppermost chalk is Pecan Gap and lies unconformably on the Austin chalk which makes up the lower portion of the walls of the pit. The contact between the two chalks can be clearly seen and is illustrated in Figure 2. The top of the Austin is here marked by numerous *Gryphaea aucella* and is composed of soft, white, granular chalk. The overlying Pecan which here forms a capping ledge is a harder, somewhat massive cream-colored chalk having a conchoidal fracture. A similar situation is present in the quarry at Cementville, at the northwestern edge of the city of San Antonio;

and here also the unconformity between the two chalks can be clearly seen.

West of San Antonio the Pecan Gap chalk continues to lie immediately upon the Austin chalk and embraces the upper portion of what has previously been mapped as Austin; the top of the Austin being now definitely established by *Gryphaea aucella*.

Medina County.—In this county, the Pecan Gap chalk has already merged with the Anacacho limestone of the Rio Grande em-

FIG. 2.—Exposure in Longhorn Quarry, near Fratt, showing contact of Pecan Gap and Austin chalks.

bayment. The *Diploschiza* zone can be seen, however, in two particularly good exposures and here marks the approximate top of the Anacacho limestone according to Stephenson.[21] The first of these exposures is in the bank of Medina River at Castroville (locality 51 in Figure 1). The rock is soft, thin-bedded, white-to-gray chalk and slightly sandy chalky marl. The other of these exposures (locality 52 in Figure 1) is in Seco Creek approximately 3 miles north of D'Hanis. Here the *Diploschiza cretacea* zone, including specimens of *Diploschiza cretacea*, is exposed at the top of the hard cream-white crystalline limestone of the Anacacho in the lower portion of the creek bank; and is overlain by a thin bed of clay which is in turn covered by a cream-

[21] L. W. Stephenson, personal communication.

colored sandy, glauconitic, irregularly indurated marl. As one proceeds north up the creek the limestone is completely covered by the overlying younger beds.

BOLIVINA INCRASSATA ZONE

The *Bolivina incrassata* zone which contains an abundance of *Bolivina incrassata* Reuss is the upper or youngest of the three zones of the Pecan Gap chalk. The type locality of this zone is in a small creek at the crossing of the Ladonia-Commerce Highway 2 miles south of Ladonia in Fannin County (locality 16 in Figure 1). The beds here are composed of soft, medium-bedded, white-to-cream-colored chalk which breaks with a conchoidal fracture. *Inoceramus* sp. is the most common megascopic fossil noted. The beds contain abundant *Foraminifera*. The foraminiferal assemblage of this zone is as follows.

Anomalina complanata Reuss
Anomalina pertusa (Marsson)
Anomalina involuta (Reuss)
Arenobulimina presli (Reuss)
Anomalina rubiginosa Cushman
Astacolus taylorensis Plummer
Bolivinoides decorata Jones var. *delicatula* Cushman
Buliminella carseyae Plummer
Cibicides excolata (Cushman)
Clavulina clavata Cushman
Clavulina trilatera Cushman
Dentalina aculeata d'Orbigny
Dentalina megapolitana Reuss
Dentalina soluta Reuss
Dorothia bulletta (Carsey)
Eouvigerina gracilis Cushman
Flabellina interpunctata von der Marck
Flabellina projecta (Carsey)
Globigerina cretacea d'Orbigny
Globigerinella asper (Ehrenberg)
Globotruncana arca (Cushman)
Globotruncana canaliculata (Reuss)
Globotruncana canaliculata (Reuss) var. *ventricosa White*
Globotruncana fornicata Plummer
Globorotalia micheliniana (d'Orbigny)
Globulina lacrima Reuss
Gumbelina globulosa (Ehrenberg)
Gumbelina striata (Ehrenberg)
Gumbelina tessera (Ehrenberg)
Gyroidina umbilicata (d'Orbigny)
Heterostomella faveolata (Marsson)
Heterostomella stephensoni (Cushman)
Lagena acuticosta Reuss
Lenticulina rotulata Lamarck
Marginulina intermedia (Philippi)
Marssonella ellisorae Cushman ms. sp.
Marssonella oxycona (Reuss)
Nodosaria affinis Reuss
Planulina taylorensis (Carsey)
Pseudouvigerina plummerae Cushman
Pullenia quinqueloba (Reuss)

Saracenaria italica De France
Spiroplectammina anceps (Reuss)
Spiroplectoides rosula (Ehrenberg)
Textularia ripleyensis W. Berry
Valvulineria cf. *umbilicatula* (d'Orbigny)
Ventilabrella carseyae Plummer
Astocolus crepidulus (Fichtel & Moll)
Bolivina incrassata Reuss
Bolivinita eleyi Cushman
Bulimina minuta (Marsson)
Bulimina obtusa d'Orbigny
Bulimina trochoides (Reuss)
Cibicides involuta (Reuss)
Cibicides wuellerstorfi (Schwager)
Clavulina insignis Plummer
Cornuspira cretacea Reuss
Dentalina annulata (Reuss)
Dentalina cf. *consobrina* d'Orbigny
Dentalina legumen (Reuss)
Eponides cf. *tenera* (Brady)
Clavulina plummerae Sandidge
Frondicularia archiciana d'Orbigny var. *strigillata* Bagg
Frondicularia cordai Reuss
Frondicularia golfussi Reuss
Frondicularia lanceola Reuss
Frondicularia verneuliana d'Orbigny
Frondicularia gracilis Franke
Globotruncana calcarata Cushman
Hemicristellaria ensis (Reuss)
Lituola taylorensis Cushman & Waters
Marginulina bullata Reuss
Marginulina elongata d'Orbigny
Nodosaria intercostata Reuss
Nodosaria radicula (Linne)
Pleurostomella subnodosa Reuss
Pyrulina cylindroides (Roemer)
Pulvinulinella alata (Marsson)
Ramulina globulifera H. B. Brady
Robulus munsteri (Reuss)
Vaginulina strigillata (Reuss)
Valvulineria allomorphinoides (Reuss)

In addition to this locality the *Bolivina incrassata* zone is present at White Cliffs in Arkansas as previously described, and at many other localities in Texas. A discussion of some of the more representative localities in Texas follows.

Red River County.—In 1932 H. N. Spofford pointed out the existence of several isolated chalk outcrops in northeastern Red River County and northwestern Bowie County.[22] An examination of samples from two of these localities revealed that they were a part of the *Bolivina incrassata* zone. One of these exposures is under a culvert at the Henrietta School (locality 5 in Figure 1), 1 mile west of Henrietta Church; the other is on the Pine Springs-Avery road 0.2 mile south of Mill Creek in Bowie County. The rock at each of these localities is

[22] H. N. Spofford, "Pecan Gap Chalk, New Localities in Red River and Bowie Counties," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 2 (February, 1932), pp. 212–14.

composed of soft, white-to-cream-colored chalk having conchoidal fracture.

Delta County.—The *Bolivina incrassata* zone is represented here by one good exposure in a quarry 1 mile north of Lake Creek (locality 13 in Figure 1). The rock is massive, fairly hard, blue-white chalk which breaks with a conchoidal fracture. The rock is also exposed just north of the town of Enloe, but the exposures are very poor and the rock is badly weathered.

Collin County.—The exposure of the *Bolivina incrassata* zone in Fannin County has already been discussed. The zone crops out next in Collin County and at one locality in Hunt County close to the Collin County line. There are three exposures of this zone in and around the town of Farmersville. One (locality 19 in Figure 1) is in a cut on the G.C. & S.F. Railroad on the north edge of the town; another is in the ditch at the turn of a local road 1 mile northeast of Farmersville post office; the third is in a cut on the M.K. & T. Railroad 1 mile east of Farmersville. The rock at all of these localities is a soft, bluish or brownish white chalky marl. The material weathers easily, and appears to have considerable clay in its matrix.

Southeast of Farmersville, near the Hunt-Collin county line, is another group of exposures which contain the fauna of the *Bolivina incrassata* zone. One of these localities is on the county line 0.3 mile south of the M.K. & T. Railroad. Another (locality 18 in Figure 1) is in Hunt County 1.5 miles south of the M.K. & T. Railroad and 0.3 mile east of the Collin County line. Two others are on secondary roads 3.8 miles southeast of Farmersville. All of these localities expose soft, white-to-cream-colored, medium-bedded chalk. The rock breaks with conchoidal fracture and appears rather massive.

In the southern portion of Collin County, the *Bolivina incrassata* zone forms a more or less definite band along the eastern edge of the Pecan Gap outcrop and is the beginning of the well developed outcrop of this zone which extends southward across Rockwall County. The exposures all show massive, medium-bedded, fairly hard, cream-colored chalk containing numerous fossil shell fragments, chiefly *Inoceramus* sp. and abundant *Foraminifera.* Typical localities may be seen in a small creek where it approaches a road 0.4 mile east and 1.4 miles north of the town of Nevada; and in a deep wash just south of an east-west road 1.3 miles south of Nevada.

Rockwall County.—The outcrop of the *Bolivina incrassata* zone is well developed in Rockwall County where it forms a chalk band from the north to the south part of the county and is separated from the *Flabellammina compressa* zone by marly clays containing a scant fauna.

The abundant fauna of the *Diploschiza cretacea* or middle zone which normally should lie between these two zones is absent, possibly due to depositional conditions. Like the *Flabellammina compressa* zone, the *Bolivina incrassata* zone here has an excessively wide outcrop, due probably to an extremely flat dip. The chalk forms a band of varying width across the county from Nevada in Collin County, on the north, into Kaufman County on the south. This band lies 1 mile west of the town of Fate and a little more than 2 miles west of the town of Chisholm. Thus the upper limits of the Pecan Gap outcrop in Rockwall County are appreciably farther east than has formerly been supposed; and also the entire width of outcrop is abnormally wide.

The rock of the *Bolivina incrassata* zone here is pure chalk in all its exposures. The hardness and degree of massiveness varies locally, but otherwise the formation is uniformly white-to-cream-colored chalk. Typical exposures may be seen at several places throughout the county, notably in a deep ditch on the south side of a small road 1.3 miles northwest of Fate, on the south side of a road 0.7 mile east of Union School (locality 22 in Figure 1) and in an excavation in a small pasture midway between the towns of Chisholm and Heath. The species of *Foraminifera* found at locality 22 are listed in column number 11 in the check list.

Kaufman County.—The *Bolivina incrassata* zone here is not as prominent as in Rockwall County on the north. Nevertheless it is present at several localities, and wherever found the rock is white-to-cream-colored slightly argillaceous chalk. In most places it is hard, although this varies locally. Good exposures of the chalk can be observed in a small creek 3.2 miles northeast of Forney near the center of the Juan Lopez Survey; in a ditch on the Forney-Crandall road 3 miles north of Crandall; and in a creek 3.2 miles west of Talty in the southwest quarter of the Stephen White Survey (locality 25 in Figure 1).

Navarro County.—With the exception of two isolated localities in the central portion of this county, the *Bolivina incrassata* zone does not extend farther southwest than Kaufman County. The northernmost of these localities (locality 28 in Figure 1) is in a dry branch beside a local road 1.8 miles south of Barry. Here the formation is brownish white soft chalky marl grading into a blue-gray very argillaceous chalk near the base of the exposure. The other locality (number 29 in Figure 1) is the upper portion of the formation exposed in the deep gulches 1 mile south of Cottonwood Creek. The lithologic character of this locality has already been described under the heading of the *Flabellammina compressa* zone and need not be repeated here.

PALEONTOLOGY

In working this problem a detailed study was made of the microfauna associated with the chalks. Samples from approximately 400 localities were collected throughout the area.

From these samples it was possible to determine certain characteristic zone-faunules. Check lists were prepared which show the range of the species in the three zones. The following localities are given in the check list.

UNCONFORMITIES

The Pecan Gap chalk crops out in a very narrow band through Hunt, Delta, and eastern Red River counties ranging from 1 to 2 miles wide; whereas in the area east of Clarksville the outcrop is about 4 miles wide, also 4 miles wide in Collins, Rockwall, and Kaufman counties. This variation in the width of outcrop is due to an unconformity across Hunt and Delta counties at the base of the chalk cutting out the *Flabellammina compressa* zone, which is 2 miles wide in Kaufman, Rockwall, and Collins counties. This zone makes its appearance again in Red River County just east of Fulbright. In the vicinity of White Rock, approximately 7 miles east of Clarksville, it is 1.5 miles wide. In addition to the absence of this zone, the physical evidence of an unconformity is seen at the type locality of the Pecan Gap in the railroad cut 0.5 mile east of Pecan Gap. Here phosphatic pebbles and a thin glauconitic zone with borings separate the basal *Diploschiza cretacea* zone from the Wolfe City sands. The basal *Diploschiza cretacea* zone containing phosphate nodules is found in the bed of the Cuthand Creek 4.5 miles east of Fulbright at the crossing of the road to McCoy. Here is found the zone of *Gryphaea vesicularis*, which marks the basal part of the Pecan Gap from this area west across Delta and Hunt counties. At the top of the chalk a progressive overlap from Bowie County westward transgresses older and older beds of the Pecan Gap. In western Bowie County 0.2 mile south of Mill Creek in the Pine Springs-Avery road upper Taylor clays are separated from the *Bolivina incrassata* zone of the Pecan Gap by a layer of phosphate pebbles and glauconitic sands. There are numerous borings down into the chalk filled with glauconite and phosphatic nodules. Eleven miles due west the upper Taylor clays rest unconformably on the upper part of the *Diploschiza cretacea* zone. Approximately 3 miles southwest of Clarksville on an unnamed creek, Stephenson has found a beautiful unconformity marked by a zone of phosphatic nodules, glauconitic sands, and borings where upper Taylor clays rest on still lower beds of the *Diploschiza cretacea*

CHECK LIST OF PECAN GAP SPECIES

	Bolivina Incrassata Zone			*Diploschiza Cretacea Zone*										*Flabellammina Compressa Zone*			
	1	11	9	2	3	8	4	12	13	14	15	16	17	10	7	6	5
1. *Anomalina complanata* Reuss	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
2. *Anomalina involuta* (Reuss)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
3. *Anomalina rubiginosa* Cushman	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
4. *Anomalina pertusa* (Marsson)	x	x	x	x	x	x	x	x	x	x	x	x	x				
5. *Arenobulimina presli* (Reuss)	x	x	x	x	x	x	x	x	x	x	x	x	x				
6. *Astacolus taylorensis* Plummer	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
7. *Bolivinoides decorata* Jones var. *delicatula* Cushman	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
8. *Buliminella carseyae* Plummer	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
9. *Cibicides excolata* (Cushman)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
10. *Clavulina clavata* Cushman	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
11. *Clavulina trilatera* Cushman	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
12. *Dentalina aculeata* d'Orbigny	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
13. *Dentalina megapolitana* Reuss	x	x	x	x	x	x	x	x	x	x		x	x				
14. *Dentalina soluta* Reuss	x	x		x	x	x	x	x	x	x	x	x	x	x			
15. *Dorothia bulletta* (Carsey)	x	x	x	x	x	x	x	x	x	x	x	x	x				
16. *Eouvigerina gracilis* Cushman	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
17. *Flabellina interpunctata* von der Marck	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
18. *Flabellina projecta* (Carsey)	x	x	x	x		x	x	x	x	x	x	x	x			x	x
19. *Globigerina cretacea* d'Orbigny	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
20. *Globigerinella asper* (Ehrenberg)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
21. *Globotruncana arca* (Cushman)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
22. *Globotruncana canaliculata* (Reuss)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
23. *Globotruncana canaliculata* (Reuss) var. *ventricosa* White	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
24. *Globotruncana fornicata* Plummer	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
25. *Globorotalia micheliniana* (d'Orbigny)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
26. *Globulina lacrima* Reuss	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

CHECK LIST OF PECAN GAP SPECIES

	Bolivina Incrassata Zone			*Diploschiza Cretacea Zone*										*Flabellammina Compressa Zone*			
	1	11	9	2	3	8	4	12	13	14	15	16	17	10	7	6	5
27. *Gumbelina globulosa* (Ehrenberg)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
28. *Gumbelina striata* (Ehrenberg)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
29. *Gumbelina tessera* (Ehrenberg)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
30. *Gryoidina umbilicata* (d'Orbigny)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
31. *Heterostomella faveolata* (Marsson)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
32. *Heterostomella stephensoni* (Cushman)	x	x	x	x	x	x	x	x	x	x	x	x	x				
33. *Lagena acuticosta* Reuss	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
34. *Lenticulina rotulata* Lamarck	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
35. *Marginulina intermedia* (Philippi)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
36. *Marssonella ellisorae* Cushman ms. sp.	x	x		x	x	x	x	x	x	x	x	x	x				x
37. *Marssonella oxycona* (Reuss)	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x
38. *Nodosaria affinis* Reuss	x	x		x		x	x	x	x	x	x	x	x	x	x	x	x
39. *Planulina taylorensis* (Carsey)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
40. *Pseudouvigerina plummerae* Cushman	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
41. *Pullenia quinqueloba* (Reuss)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
42. *Saracenaria italica* De France	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
43. *Spirioplectammina anceps* (Reuss)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
44. *Spiroplectoides rosula* (Ehrenberg)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
45. *Textularia ripleyensis* W. Berry	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
46. *Valvulineria* cf. *umbilicatula* (d'Orbigny)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
47. *Ventilabrella carseyae* Plummer	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
48. *Astacolus crepidulus* (Fichtel & Moll)	x	x	x														
49. *Bolivina incrassata* Reuss	x	x	x														
50. *Bolivinita eleyi* Cushman	x	x	x	x	x		x	x	x	x	x	x	x	x	x		x
51. *Bolivinita planata* Cushman			x											x			
52. *Bulimina minuta* (Marsson)	x	x		x	x	x	x	x	x	x	x	x	x				
53. *Bulimina obtusa* d'Orbigny	x	x	x								x	x					

CHECK LIST OF PECAN GAP SPECIES

	Bolivina Incrassata Zone			*Diploschiza Cretacea Zone*										*Flabellammina Compressa Zone*			
	1	11	9	2	3	8	4	12	13	14	15	16	17	10	7	6	5
54. *Bulimina trochoides* (Reuss)	x	x			x	x	x	x	x	x	x	x	x				x
55. *Cibicides involuta* (Reuss)	x	x	x	x	x	x	x	x	x	x	x	x	x				
56. *Cibicides wuellerstorfi* (Schwager)	x	x	x	x		x	x	x	x	x	x	x	x				
57. *Clavulina insignis* Plummer	x	x		x	x	x	x	x	x	x	x	x	x	x	x		
58. *Cornuspira cretacea* Reuss	x	x				x	x				x	x	x				
59. *Dentalina annulata* (Reuss)	x	x					x	x	x	x	x	x	x	x			
60. *Dentalina* cf. *consobrina* d'Orbigny	x	x			x	x	x		x	x	x	x	x	x		x	x
61. *Dentalina legumen* (Reuss)	x	x		x			x	x	x	x	x	x	x	x			
62. *Dorothia stephensoni* Cushman ms. sp.		x			x		x	x	x	x	x	x	x				
63. *Eponides* cf. *tenera* (Brady)	x	x		x			x				x	x	x				x
64. *Clavulina plummerae* Sandidge	x		x				x				x		x				x
65. *Frondicularia archiciana* d'Orbigny var. *strigillata* Bagg	x	x		x	x	x	x	x	x	x	x	x					
66. *Frondicularia cordai* Reuss	x	x	x							x	x	x	x				
67. *Frondicularia golfussi* Reuss	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x
68. *Frondicularia lanceola* Reuss	x	x		x			x	x	x			x	x				
69. *Frondicularia verneuliana* d'Orbigny	x	x		x	x	x	x	x	x	x	x	x	x	x	x		x
70. *Frondicularia gracilis* Franke	x	x		x	x		x	x	x	x	x	x	x	x	x		x
71. *Globotruncana calcarata* Cushman	x	x	x														
72. *Hemicristellaria ensis* (Reuss)	x			x		x	x	x	x	x	x	x	x	x		x	x
73. *Lituola taylorensis* Cushman & Waters	x	x		x	x	x	x	x	x	x	x	x	x				
74. *Marginulina bullata* Reuss	x	x		x	x	x	x	x	x	x	x	x	x			x	x
75. *Marginulina elongata* d'Orbigny	x	x		x	x	x	x	x	x	x	x	x	x				
76. *Nodosaria intercostata* Reuss	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x
77. *Nodosaria radicula* (Linné)	x	x				x	x	x	x	x	x	x	x				
78. *Pleurostomella subnodosa* Reuss	x	x	x	x	x	x	x	x	x	x	x	x	x				
79. *Pyrulina cylindroides* (Roemer)	x	x	x	x	x	x	x	x	x	x	x	x	x				

CHECK LIST OF PECAN GAP SPECIES

	Bolivina Incrassata Zone			*Diploschiza Cretacea Zone*										*Flabellammina Compressa Zone*			
	1	11	9	2	3	8	4	12	13	14	15	16	17	10	7	6	5
80. *Pulvinulinella alata* (Marsson)	X			X	X	X					X	X	X	X	X		X
81. *Ramulina globulifera* H. B. Brady	X	X	X	X	X	X	X	X	X	X	X	X	X				
82. *Robulus megalopolitana* (Reuss)				X		X	X	X	X	X	X	X	X				
83. *Robulus münsteri* (Reuss)	X	X	X	X		X	X	X	X	X	X	X	X				X
84. *Vaginulina strigillata* (Reuss)	X	X									X	X					
85. *Valvulineria allomorphinoides* (Reuss)	X	X		X		X	X	X	X	X	X	X					
86. *Flabellammina compressa* (Beissel)		X		X	X		X	X	X	X	X	X	X	X	X	X	X
87. *Frondicularia archiciana* d'Orbigny		X		X	X	X	X	X	X	X	X	X	X			X	
88. *Frondicularia verneuliana* d'Orbigny var. *bidentata* Cushman				X			X	X	X	X	X	X	X				
89. *Frankeina cushmani* Alexander & Smith		X		X			X	X	X	X		X		X	X	X	X
90. *Gaudryina bentonensis* (Carmon)		X					X				X	X	X	X	X	X	X
91. *Gaudryina rugosa* d'Orbigny		X									X	X					
92. *Lingulina furcillata* Berthelin		X						X			X	X					
93. *Nodosaria obscura* Reuss		X	X	X	X	X	X	X	X	X	X	X	X	X	X		X
94. *Textularia* sp. A		X		X			X	X	X	X	X	X	X				
95. *Tritaxia ellisorae* Cushman ms. sp.		X		X	X		X	X	X	X	X	X	X				
96. *Clavulina compressa* Cushman				X			X	X	X	X	X	X	X	X	X		
97. *Clavulina disjuncta* Cushman				X		X	X	X	X	X	X	X	X				
98. *Flabellina rugosa* d'Orbigny				X	X	X	X	X	X	X	X		X		X	X	X
99. *Globulina lacrima* Reuss var. *horrida* Reuss				X	X	X	X	X	X	X		X					X
100. *Kyphopyxa christneri* (Carsey)				X	X	X	X	X	X	X			X	X	X	X	X
101. *Planularia tricarinella* (Reuss)				X		X	X				X	X	X				
102. *Gyroidina depressa* (Alth)									X	X	X	X	X				
103. *Haplophragmoides rugosa* Cushman & Waters				X				X	X	X	X	X					
104. *Loxostoma clavata* (Cushman)							X	X	X	X			X	X	X	X	X
105. *Nonionella cretacea* Cushman						X	X				X	X		X	X	X	X
106. *Gaudryinella capitosa* Cushman														X	X	X	X

No. 1. Top of bluff at White Cliffs, Arkansas.
No. 2. Base of Taff's Division #2 of White Cliffs Bluff
No. 3. *Vesicularis* bed, Division #4 of White Cliffs Bluff.
No. 4. Loc. 7 on Lawson Creek at bridge on Clarksville-Texarkana Highway, Red River County, Texas.
No. 5. White Rock, Red River County, Texas.
No. 6. In town of Clarksville a few blocks south of the Paris Highway.
No. 7. 0.7 mile southwest of McCoy, Red River County.
No. 8. In G. C. & S. F. R. R. cut 0.5 mile east of Pecan Gap, Texas.
No. 9. In G. C. & S. F. R. R. cut north edge of Farmersville, Texas.
No. 10. On Forney-Mesquite road 0.7 mile west of Forney in Kaufman County.
No. 11. On road 0.7 mile east of Union School, Rockwall County.
No. 12. Northwest edge of City of Marlin, Falls County, Texas.
No. 13. On road 2 miles southeast of Westphalia, Falls County, Texas.
No. 14. In Creek bed, 1.6 miles south of Rogers.
No. 15. In excavation point one mile west of Taylor city limits on old Highway #43, Williamson County, Texas
No. 16 South bank of Brushy Creek, 1.75 miles above Rice's Crossing, Williamson County, Texas.
No. 17. On Highway #20, 0.6 mile east of Big Walnut Creek, Travis County.
Localities numbers 1, 11, 9 are the *Bolivina incrassata* zone. Numbers 2, 3, 4, 8, 12, 13, 14, 15, 16, 17 are the *Diploschiza cretacea* zone, and numbers 5, 6, 7, and 10 are the *Flabellammina compressa* zone.

zone. Still farther west at a point 1 mile northeast of Gintown the Taylor clays rest on the *Gryphaea vesicularis* horizon or basal part of the *Diploschiza cretacea* zone. In addition to these unconformities other structural conditions are possibly present which also influence the variation in the width of the outcrop of the Pecan Gap across Red River County.

SUBSURFACE CORRELATIONS

The Pecan Gap chalk is an extremely good horizon marker for subsurface work because of its general occurrence and definite characteristics. As can be seen by the accompanying cross section (Fig. 3) made along the line A-A' as shown in Figure 1, it is possible to trace the Pecan Gap chalk in wells over the entire area defined by the surface outcrop. Corresponding with the surface outcrops the chalk varies in thickness from place to place. The maximum thickness of the chalk, 380 feet, occurs in wells in Bowie County at the northeastern end of the Texas outcrop. In Medina and western Bexar counties, which constitute the southwestern end of the Pecan Gap outcrop, the chalk has a thickness of 280 feet. Between these two extremes the chalk varies in thickness from as little as 50 or 60 feet in Guadalupe, Caldwell, and Kaufman counties to as much as 350 feet in Falls County. The cross section also shows three chalks in north Texas, the Pecan Gap, the Gober, and the Austin.

In Kaufman County the Gober chalk gradually merges into the Austin chalk. In the wells from Kaufman County to Guadalupe County the assemblage of *Foraminifera* found in the upper part of the so-called Austin chalk is the same as that found in the Gober chalk. West of Gaudalupe County the Pecan Gap in the wells rests unconformably on the *Gryphaea aucella* bed of the Austin. As stated previously, the first place in the field this unconformity is noted is near Selma, where the *Gryphaea aucella* bed of the Austin chalk is exposed in Cibolo Creek and the Pecan Gap chalk is present in the near-by hills. In the Longhorn Cement Pit at San Antonio the actual contact is seen.

In the banks of Little Walnut Creek east of Austin on the Austin-Manor Highway the assemblage of *Foraminifera* present in the chalk above the *Gryphaea aucella* bed of the Austin includes the characteristic species of the Gober chalk. In the upper part of the chalk mapped as Austin through Bell and Falls counties the foraminiferal assemblage is Taylor in age and the same as that found in the Gober chalk.

It is the senior writer's belief that the *Gryphaea aucella* bed marks

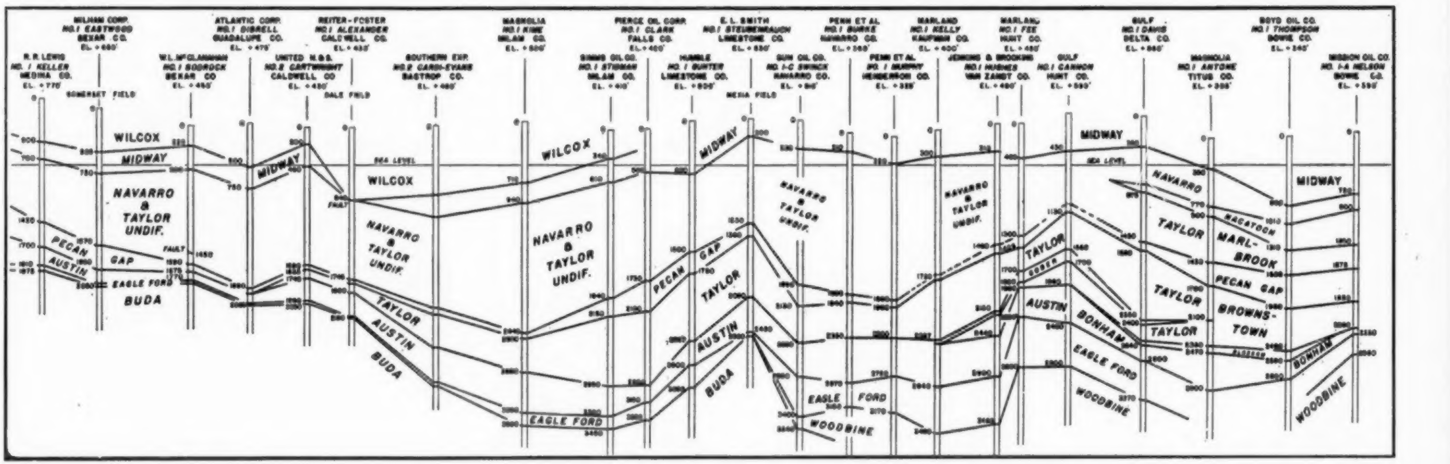


FIG. 3.—Subsurface section AA' (Fig. 1), Medina County to Bowie County. Depths in feet. Horizontal scale: 1 inch = 57.6 miles.

the top of the Austin, and the chalk in Little Walnut Creek above the *Gryphaea aucella* bed is the equivalent of the Gober, which in north Texas is separated from the Austin by the Brownstown. Figure 4 is a diagrammatic section showing the relation of the Pecan Gap, Gober, and Austin chalks.

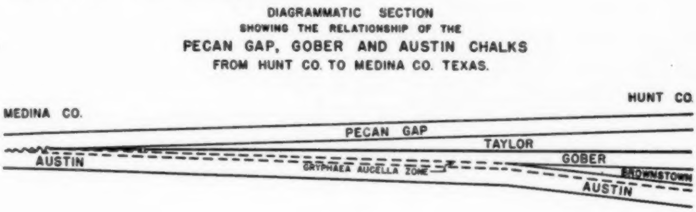


FIG. 4

RECAPITULATION

From the foregoing, it becomes apparent that the chalk section which is exposed at White Cliffs, Arkansas, is present in its entirety in Texas, that it can be divided into three faunal zones on the basis of microfauna, that the chalk exposed at Pecan Gap in Delta County is included in the lower portion of the bluff at White Cliffs (93 feet below the top of the bluff), and that the chalk can be traced from White Cliffs, Arkansas, across northeast Texas to Hunt County and then southward and southwestward to where it merges into the top of the Anacacho limestone in Medina County, Texas.

There are several other interesting features. Most important of these is the fact that whereas the Pecan Gap chalk occurs several hundred feet above the Austin chalk equivalent in east and northeast Texas, in the San Antonio area the upper portion of the formation now mapped as Austin chalk is in reality Pecan Gap.

Another interesting point brought out by this work is the presence of two series of unconformities. One, at the base of the Pecan Gap chalk between it and the underlying Wolfe City, extends from Collin County eastward to a point east of White Rock in Red River County. The other, at the top of the Pecan Gap between it and the overlying Taylor, extends through Red River and Bowie counties. Both unconformities can be recognized by the presence of phosphate nodules, bore holes in the chalk filled with material from the formation above, and in some localities by thin conglomerate at the point of contact between the two formations. Several good exposures of both unconformities can be seen. The lower unconformity, exposed in the railroad

cut east of Pecan Gap (locality 15 in Figure 1) has already been described. The upper unconformity, exposed best on the Pine Springs-Avery road 0.2 mile south of Mill Creek, has already been described also at the locality described on a small creek 3 miles southwest of Clarksville.

Finally, it is evident from field work that the width of the outcrop of the Pecan Gap chalk was influenced in many places by structural features. Much more detailed work will have to be done before the full extent of these is known. In this paper, which is primarily for the purpose of correlation, such a study was not possible. It remains for future work to answer these questions; and it is hoped that the present work may be of some assistance when that work is attempted.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 11 (NOVEMBER, 1934), PP. 1537-1543, 5 FIGS.

GEOLOGICAL NOTES

NOTES ON UPPER MISSISSIPPIAN ROCKS IN TRANS-PECOS TEXAS[1]

Rocks of Mississippian age were first reported in trans-Pecos Texas by Beede in 1920[2] when he described, as the Helms formation, rocks in the Hueco Mountains that had hitherto been mapped as Pennsylvanian. The fauna was studied by Weller,[3] who considered it to be of upper Mississippian or Chester age. This determination has since been confirmed by G. H. Girty, after studying collections made from the same beds by himself and other members of the United States Geological Survey. The purpose of this note is to give further information on the occurrence of later Mississippian rocks in this part of Texas.

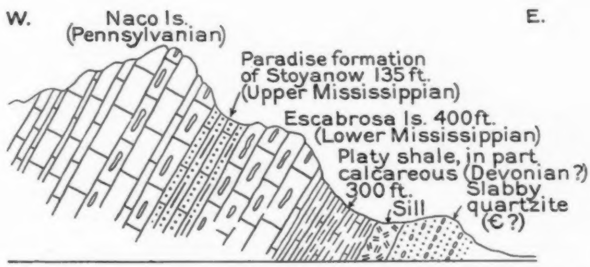


FIG. 1.—Section on east side of Chiricahua Mountains, north of Portal P. O., southeastern Arizona.

Hueco Mountains.—In the Hueco Mountains, the rocks lying between the limestones of Silurian and Pennsylvanian age are 500–700 feet thick, and constitute the Helms formation as now defined. A typical succession at one of the more accessible localities is shown in Figure 1. At the base are 150 feet of white cherts and greenish shales, for which R. E. King and the writer some years ago suggested a

[1] Published by permission of the director, United States Geological Survey.

[2] J. W. Beede, "Notes on the Geology and Oil Possibilities of the Northern Diablo Plateau in Texas," *Univ. of Texas Bull. 1852* (1920), pp. 7–8.

[3] Beede cited only a few fossils from the formation, but a more detailed description of the same collection by Stuart Weller has been given by Schuchert in "The Pennsylvanian-Permian Systems of Western Texas," *Amer. Jour. Sci.*, 5th Ser., Vol. 14 (1927), pp. 383–84.

Devonian age,[4] but from which no fossils have so far been collected. Overlying these are 300 feet of slabby limestones, gray and cherty below, and changing to brown and sandy above. These contain few fossils other than crinoidal fragments, but in 1931, J. B. Knight and the writer collected one or two brachiopods from the upper sandy part which Girty considers to be of upper Mississippian age. Between these and the limestones of Pennsylvanian age above are about 200 feet of shales, sandy shales, slabby brown sandstones and yellowish thin limestones. The main collections of upper Mississippian fossils in the Helms formation have been made in these thin limestones, and include various bryozoans such as *Archimedes*, numerous brachiopods, and some pelecypods and trilobites.

Franklin Mountains.—In the Franklin Mountains, which are the

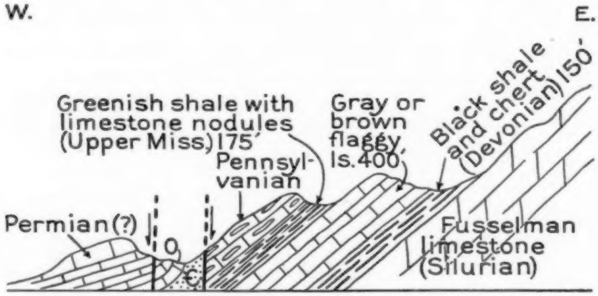


FIG. 2.—Section on west side of Franklin Mountains north of El Paso, and 6 miles east-northeast of Canutillo, Texas.

next range west of the Hueco Mountains, rocks of Carboniferous age crop out in the northern part along the western foothills, and dip steeply to the west[5] as shown in Figure 2. As noted, beds of Mississippian age have been suspected in this area for a number of years. Moreover, in 1928, N. H. Darton, when on an excursion with R. E. King and the writer, noted the resemblance of the beds immediately above the Silurian limestones to the Percha shale of New Mexico, and collected a few fossils which suggested that these were of Devonian age.[6] The rocks on the west slope of the Franklin Mountains are now being studied in detail by L. A. Nelson, of the Texas College of Mines at

[4] P. B. King and R. E. King, Stratigraphy of the Outcropping Carboniferous and Permian Rocks of Trans-Pecos Texas, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), p. 910.

[5] G. B. Richardson, El Paso folio. *U. S. Geol. Survey Geol. Atlas* (No. 166), 1909.

[6] N. H. Darton, "Devonian Strata in Western Texas" (abstract), *Bull. Geol. Soc. Amer.*, Vol. 40 (1929), pp. 116–17.

El Paso, and he has made large collections of beautifully preserved fossils from different zones in the limestones of Pennsylvanian age in the district. In the summer of 1933, through the courtesy of Professor Nelson, the writer was enabled to visit the section again at a place about a mile north of the locality seen in 1928, and about 6 miles due east of Vinton, Texas. On this trip, further collections were made from the beds lying between the Silurian and Pennsylvanian limestones.

Resting on the Silurian limestones are 150 feet of strata, largely black cherts below, but passing upward into black shales and interbedded black limestones. Except for their prevailingly black color, these beds are not unlike those which directly overlie the Silurian in the Hueco Mountains. The limestones contain discinoid brachiopods, and in addition, *Styliolina*, *Ambocoelia*, and *Spirifer*. According to Edwin Kirk, who has examined these fossils, "there seems to be no question but that the material is of Devonian age." Nelson reports that he has collected cephalopods from these same beds at another locality.

Overlying these beds are about 400 feet of flaggy gray or brown limestones, in places cherty, in others sandy. In the lower part are also some lenticular beds of massive, gray, coarsely crystalline crinoidal limestone. From a bed about a third of the distance up in the limestones were collected *Leiorhynchus carboniferum* ?, *Spirifer* aff. *arkansanus*, *Spirifer* sp., and *Composita* ? sp. Girty, who identified this material, considers it to be of upper Mississippian or at least post-Madison age.

Between these limestone beds, and those of Pennsylvanian age above, are 175 feet of greenish shale, with some sandy seams, and near the top interbedded nodular, yellowish, earthy, very fossiliferous limestones. From these, Girty has tentatively identified the following assemblage of fossils.

Fenestella sp.
Cystodictya aff. *lineata*
Rhipidomella sp.
Schizophoria n. sp.
Chonetes sp.
Productus ovatus
Productus aff. *parvus*
Productus aff. *inflatus*
Productus semireticulatus
Avonia oklahomensis
Avonia aff. *arkansana*
Pustula aff. *biseriata*
Pustula aff. *hirsutiformis*
Ambocoelia sp.
Reticularia sp.
Platyceras sp.
Griffithides sp.
Ostracoda indet.

Girty states that, although the "identifications are in places somewhat sketchy and in some instances will without doubt be changed when better specimens are available, . . . the age determination is safe," and that the fossils are "clearly of upper Mississippian age, and represent the Helms formation."

New Mexico and Arizona.—North and northwest of the Franklin Mountains, rocks of Devonian age (Percha shale), and rocks of lower Mississippian age (Lake Valley limestone) are present in many of the mountain ranges in the southern part of New Mexico.[7] There appears, however, to be no representative of upper Mississippian rocks like those in the Franklin and Hueco Mountains. The precise relation of the lower and upper Mississippian rocks in the region is therefore in doubt. Some years ago R. E. King and the writer suggested that its equivalent might be found in the middle limestones of the Helms formation in the Hueco and Franklin Mountains,[8] and the appearance in the lower part of these beds at the last place of massive crinoidal limestones would apparently suggest an interfingering of the Lake

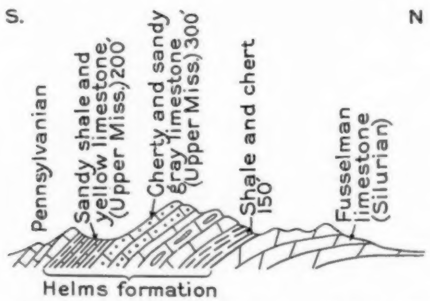


FIG. 3.—Section in Hueco Mountains, 24 miles east-northeast of El Paso, Texas, and immediately north of El Paso-Carlsbad Highway.

Valley facies toward the northwest. The few fossils so far collected in the middle limestones, however, suggest upper rather than lower Mississippian age.

Rocks of upper Mississippian age have been found by Stoyanow[9] at one locality in southeastern Arizona. On the east side of the Chiricahua Mountains, on a ridge north of Portal Post Office (Fig. 3), there intervene between the Escabrosa limestone (lower Mississippian) and the Naco limestone (Pennsylvanian and Permian) about 135 feet of brownish, fine-grained shaly sandstone, interbedded with brown or yellowish compact to finely crystalline fossiliferous limestone. These have been called by Stoyanow, the Paradise formation,

[7] N. H. Darton, " 'Red Beds' and Associated Formations of New Mexico," *U. S. Geol. Survey Bull. 794* (1928), pp. 16–18.

[8] King and King, *op. cit.*, Fig. 2, p. 909.

[9] A. A. Stoyanow, "Notes on Recent Stratigraphic Work in Arizona," *Amer. Jour. Sci.*, 5th Ser., Vol. 12 (1926), pp. 316–18.

and its fauna is considered by him to be of Meramec or Chester age. According to Girty, collections made by J. B. Knight and the writer at this place in 1931 are "a characteristic upper Mississippian fauna, with *Archimedes, Diaphragmus, Brachythyris,* and other forms."

Sierra Diablo.—East of the Hueco Mountains the older Paleozoic beds disappear beneath strata of Permian (?) and Cretaceous age, but are exposed again about 100 miles southeast in the Sierra Diablo north of Van Horn. In recent years, rocks of considerable diversity of age have been found in the northern part of the mountains along the base of the escarpment beneath unconformably overlying Permian limestones. West of the Figure Two Ranch, limestones[10] and shales[11] of lower to middle Pennsylvanian age have been described and northwest of it limestones of Ordovician and Silurian age (Montoya and Fusselman) and cherts of possible Devonian age.[12] The writer and J. B. Knight mapped the district in detail in 1931, and collected fossils at various places.

In 1933, in reporting on an excursion of the Midland Geological Society, E. H. Sellards suggested[13] that some dark shales northwest of the ranch were of Mississippian age, and a little farther north, at a projecting angle of the mountains, described a section at whose base were

> chert-bearing limestones, overlain by a considerable section of dark shales and containing a few brachiopods, conodonts, and some other fossils. Above the shales are sandstones, and these in turn are overlain by the Montoya limestone.

Through the courtesy of Sellards, the fossils collected from the dark shale were sent to the United States Geological Survey for examination, and were studied briefly by Kirk, Girty, and Roundy. Although the material is scanty, Kirk states confidently that it is younger than Ordovician, and according to Roundy the conodonts suggest a Devonian or Mississippian age. These determinations thus fail to sustain the possibility implied by Sellards that the beds might represent a hitherto undescribed formation of Ordovician age. Moreover, according to the observations of Knight and the writer, the upper shales at least are lithologically identical with those for which a Mississippian age has been suggested farther south, and two faults have been mapped which have caused duplication of the beds (Fig. 4). According to this interpretation, the lowest exposure at the foot of

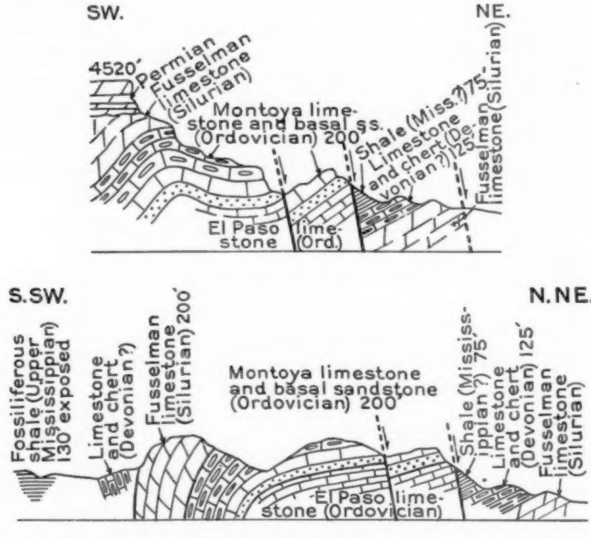
[10] King and King, *op. cit.*, p. 911.

[11] M. B. Arick, "Occurrence of Strata of Bend Age in Sierra Diablo, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16 (1932), pp. 484–86.

[12] P. B. King, "Possible Silurian and Devonian Strata in the Van Horn Region, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16 (1932), pp. 95–97.

[13] E. H. Sellards, "News Letter," *Bur. Econ. Geol.*, November, 1933.

the slope is the top of the Fusselman limestone (Silurian); the cherty limestones noted by Sellards follow these, and are the beds for which a Devonian age has been suggested by the writer. The overlying dark shales are in fault contact in places with the uppermost El Paso limestone (Ordovician) and in others with the basal sandstone of the Montoya limestone.



FIGS. 4 and 5.—Sections in Sierra Diablo on point of escarpment 2 miles northwest of Figure Two Ranch. Northeast ends of both sections are same, but diverge southwestward at angle of about 30°.

Toward the south, as shown in Figure 5, the Montoya and higher beds dip steeply, but in regular order, toward the southern exposure of shales noted by Sellards. The outcrops of beds above the Fusselman limestone are, however, scattered, and the dips are confusing. The southern exposure of shale is black or purplish, with some pyritic zones. There are several lenticular beds or lines of nodules of buff earthy limestone. From the limestones Knight and the writer have collected a fairly large fauna, which, according to Girty, fully confirms Sellards' suggestion of a Mississippian age. He states that the collection "represents the Helms fauna" and that its facies "recalls the fauna of the Caney shale, and Moorefield shale" of the regions farther east. He has given the following tentative list of fossils, chiefly to suggest the general character of the fauna at this place.

Triplophyllum sp.
Leiorhynchus carboniferum
Ambocoelia n. sp.
Composita trinuclea var.
Edmondia ? sp.
Leda n. sp.
Posidonia vaughani ?
Pleurotomaria ? sp.
Orthoceras sp.
Goniatites aff. *choctawensis*
Goniatites aff. *choctawensis* var.
Gastrioceras aff. *newsomi*

In addition, several beautifully preserved fish teeth were collected.

Summary.—This survey shows that rocks of upper Mississippian age a few hundred feet in thickness are found at various scattered localities in the southwestern United States, extending from southeastern Arizona 250 miles eastward to the Sierra Diablo in Texas. It is probable that other localities will be found with further search. The rock facies at different localities varies somewhat, being in places predominantly black shale, in others sandy shale or argillaceous sandstone, and in others slabby or nodular yellowish limestone. Some representation of the predominant facies of other areas is, however, found in all the exposures, and the beds are essentially a unit, all of which deserve the same formation name.

The known exposures are still too few to tell much about the source of the clastic sediments, or the form and extent of the sea in which they were laid down. Some years ago, R. E. King and the writer suggested[14] that the upper Mississippian part of the Helms might be the northwestward edge of that great mass of clastics in the Llanoria geosyncline farther southeast, the Tesnus formation. Fossil plants collected by David White and the writer from the Tesnus near Marathon suggest, however, that this formation is somewhat younger, and is to be considered as of early Pennsylvanian age; the equivalence of any part of it with the Helms must now, therefore, be regarded as unlikely. Apparently the upper Mississippian seas of trans-Pecos Texas were confined to the foreland northwest of the Llanoria geosyncline.

PHILIP B. KING

UNITED STATES GEOLOGICAL SURVEY
August 30, 1934

[14] King and King, *op. cit.*, p. 911.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 11 (NOVEMBER, 1934), PP. 1544-1548, 1 FIG.

DISCUSSION

GEOLOGY OF TWO BUTTES DOME IN SOUTHEASTERN COLORADO

In his paper, "Geology of Two Buttes Dome in Southeastern Colorado," published in the *Bulletin*, Vol. 18, No. 7 (July, 1934), pp. 860–70, C. W. Sanders, as a citation of evidence in support of his belief that the "Big sandstone" of the Two Buttes area is not equivalent to the Exeter sandstone, made the following statement: "The Exeter sandstone of the Cimarron Valley in Union County, New Mexico, is conformable with overlying undoubted Morrison beds and lenses out westward above typical Morrison-type variegated shale." This statement is in accord with the belief of Darton,[1] but does not agree with the interpretations of De Ford[2] and the writer.

FIG. 1.—Battleship Mountain, Sec. 28, T. 32 N., R. 35 E. Exeter sandstone resting unconformably on truncated beds of red sandstone and shale of Dockum group. One-half mile southeast of this locality, near southwest corner of Section 27, Exeter sandstone rests with similar unconformable relations on truncated beds of shale of Sloan Canyon formation.

In a former paper the writer[3] described the stratigraphy of the Cimarron Valley area. As shown in that article the formations exposed in this region and their relationships are as indicated in the accompanying table of formations.

[1] N. H. Darton, "'Red Beds' and Associated Formations in New Mexico," *U. S. Geol. Survey Bull. 794* (1928), p. 306.

[2] Ronald K. De Ford, "Areal Geology of Cimarron County, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 753–55.

[3] Ben H. Parker, "Clastic Plugs and Dikes of the Cimarron Valley Area of Union County, New Mexico," *Jour. Geol.*, Vol. 41, No. 1 (1933), pp. 38–51.

TABLE I
FORMATIONS OF CIMARRON VALLEY AREA

Age	*Group and Formation*	*Character*	*Thickness (Feet)*
Recent	Alluvium	Sand, gravel, and clay	0–50
Unconformity Pleistocene		Basalt in bottom of valley of Cimarron River	0–50
Unconformity Pliocene (?)		Basalt capping high mesas north of Cimarron River	150
Unconformity Upper Cretaceous	Graneros shale	Buff and dark shale with thin limestones. Exposed on plains bordering Cimarron Valley	0–50
	Dakota sandstone	Sandstone, gray-to-buff; fine conglomerate at base; lower 100 feet in many places massive, thinner beds above ripple-marked; cementing material locally highly siliceous or ferruginous	160
Lower Cretaceous	Purgatoire formation	Sandy and limy shale overlying massive, white-to-gray sandstone	30–60
Disconformity Lower Cretaceous (?)	Morrison formation	Varicolored shale with lenses of limestone, sandstone, and gypsum. Rests on (1) Todilto (?) gypsum, (2) Exeter sandstone, or (3) red beds of Dockum group	260–370
Jurassic (?)	Todilto formation (?)	Possibly represented by granular gypsum locally overlying Exeter sandstone	0–15
	Exeter sandstone	White-to-pink sandstone, massive and cross-bedded. Rests on (1) Sheep Pen sandstone, (2) shales of Sloan Canyon formation, or (3) red beds of Dockum group	0–80
Unconformity Triassic (?)	Sheep Pen sandstone	Tan-to-buff sandstone, thin-bedded-to-massive	68
	Sloan Canyon formation	Varicolored, argillaceous, and calcareous shales with thin layers of hard, gray marl and beds of red sandstone near base and top	125–150
	Dockum group	Maroon-to-purple conglomerates, sandstones, and shales with interbedded layers of white sandstone (Santa Rosa sandstone (?)) in lower portion of exposures	400+

The "typical Morrison-type variegated shale" which Sanders observed to underlie the Exeter sandstone belongs to the Sloan Canyon formation. In color these shales closely resemble some shales of the Morrison formation. They are, however, more massively bedded and more uniformly argillaceous

than are the Morrison shales. Positive evidence of a pre-Morrison age for these lower shales is found in the relations of the formations below and above the pronounced angular unconformity which occurs at the base of the Exeter sandstone (Fig. 1). Near the southwest corner of Sec. 27, T. 32 N., R. 35 E., the Exeter sandstone, which here has an almost imperceptible dip, is underlain by Sloan Canyon shales which dip in a southeasterly direction at a high rate. To the east and west of this locality the pre-Exeter folding was less pronounced and the discordance of dip between the beds below and above the unconformity at the base of the Exeter sandstone is so slight in places that it is evident only upon detailed mapping. It appears probable that examinations of the Exeter sandstone and the underlying variegated shales in localities of the latter type have given rise to the common miscorrelation of the shales of the Sloan Canyon formation with those of the Morrison formation and the inclusion of the Exeter sandstone in the Morrison formation.

BEN H. PARKER

GOLDEN, COLORADO
September 10, 1934

The writer has probably spent less time than has Parker in examinations of the Cimarron valley outcrops. This area, however, was included in a semi-detailed regional map prepared for the Shell Petroleum Corporation in 1931 (unpublished). Six or seven separate trips served only to strengthen his early impression to the effect that the Exeter sandstone was merely a lentil in the lower Morrison formation.

Parker believes that the true relations are best revealed in the area of pronounced pre-Exeter dips, which he interprets as pre-Exeter folding. The present writer believes that these discordances in dip represent pre-Exeter slumping of the large-block type. The dips on pre-Exeter beds, in the relatively small area to which these pronounced discordances are confined, have a heterogeneous, erratic pattern which cannot logically be related to true folding. The strikes are widely variant, in some instances even below single small outliers. The cause of the localization of the slump dips is not known, but their occurrence in the same area with the clastic plugs and dikes is suggestive. Parker[4] states, regarding the age of intrusion of the clastic plugs:

> If the author's hypothesis of their genesis is correct, their age is post-Sheep Pen sandstone and pre-Exeter. . . . No clastic injections into beds younger than Sheep Pen have been observed.

This would appear to relate the postulated slumping and the clastic-plug injection in age. Objections could probably be presented, however, from the standpoint of exact areal distributions.

When the Exeter sandstone is traced westward up the Cimarron valley, the sandstone can be seen to lens out, or nearly out, above beds which cannot be lithologically separated from the overlying Morrison section. The only unconformity observed by the writer in that area was not at the base of the Exeter but between the Morrison-type variegated clay shale and the underlying Triassic (Dockum) Red-beds. This unconformity is represented by a

[4] Ben H. Parker, "Clastic Plugs and Dikes of the Cimarron Valley Area of Union County, New Mexico," *Jour. Geol.*, Vol. 41, No. 1 (January–February, 1933), p. 51.

very slight but continuous angular discordance of a regional nature. Darton,[5] as noted by Parker, holds a similar interpretation. He states:

One sandstone, which lies considerably below the middle of the (Morrison) formation, has been called the Exeter sandstone by Lee. I am confident that it is the same bed that appears continuously in the southwestern part of Union County and eastern part of San Miguel County in the middle of the Morrison formation but here increased somewhat in thickness. In places, the underlying shale or clay is absent, and the sandstone lies unconformably on Triassic "Red Beds" (Dockum group) with some local discordances of dip as described by Lee. Near the center of R. 34 E. the surface of the "Red Beds" slopes down to the west, and 80 feet of what seems to be typical Morrison massive clay lies between the white sandstone (Exeter) and the eroded surface of the "Red Beds." As the lower shale is separated from the red strata of the supposed Dockum group by an unconformity, it is believed to be post-Triassic or part of the basal beds of the Morrison formation.

Correlation of the local gypsiferous beds in the Morrison formation with Todilto limestone is not unlikely but can scarcely be considered well enough substantiated to be of much help in the present problem.

The writer wishes to take this opportunity to call attention to two earlier papers referring to the geology of the Two Buttes area. G. K. Gilbert in 1896 wrote on "Laccolites in Southeastern Colorado," *Journal of Geology*, Vol. 4. Whitman Cross in 1906 published a petrographic study entitled "Prowersose (Syenitic Lamprophyre) from Two Buttes, Colorado," *Journal of Geology*, Vol. 14. Adolph Knopf, Yale University, recently directed the writer's attention to the existence of these early papers. He notes that Two Buttes is the type locality for the remarkable minette described by Cross. The writer was not aware of this, and, in fact, has not yet been able to secure either of these publications. Judging from the title of Gilbert's paper, it appears that he also regarded the Two Buttes injection as a laccolith.

C. W. SANDERS

HOUSTON, TEXAS
October 9, 1934

COALIFICATION THEORY OF ORIGIN OF OIL AND GAS

In a recent issue of *Science*[1] there appeared a short article by E. Berl entitled, "Origin of Asphalt, Oil, Natural Gas and Bituminous Coal," in which the results of the heat treatment (230°C. and more) of cellulose and other carbohydrates together with alkaline materials in the presence of water were summarized. A plastic material—"proto product"— resulting from this treatment is reported to contain aliphatic, naphthenic, and aromatic substances and gave, upon incomplete hydrogenation or incomplete cracking, an asphalt-like material. This, in turn, like natural asphalt or "material like jet," upon complete cracking or complete hydrogenation, was transformed into a mixture of aliphatic, hydroaromatic, and aromatic hydrocarbons very much like natural oil. In these experiments proto products were also obtained by the coalification of humic, saccharinic, or lactic acids. Berl reports that lignin and its derivatives failed to give similar results.

[5] N. H. Darton, "Red Beds and Associated Formations in New Mexico," *U. S. Geol. Survey Bull. 794* (1928), pp. 306–07.

[1] *Science*, New Ser., Vol. 80, No. 2071 (1934), pp. 227–28.

In interpreting the results of these experiments, Berl concludes as follows.

> Asphalts and jets are therefore intermediate stages of the transformation of the proto product into oil and are not formed from hydrocarbons through the reaction with oxygen. . . .
>
> Natural gas, asphalts, oils and bituminous coals may therefore be derived from the same substances or their derivatives—the carbohydrates formed by nature on such a great scale.
>
> The so-called animal theory, which explains the formation of oil by the heat decomposition of fish, and the lignin theory, which assumes that bituminous coals are derivatives of lignin, can not be substantiated by experiments.

The author of this theory apparently is not familiar with the geologic conditions under which oil and gas must have been formed in nature. Petroleum geologists will agree that the temperatures involved in the coalification experiments are higher than would obtain in nature except at depths normally greater than those involved in the formation of oil or except in the proximity of igneous intrusions which generally are distantly removed from commercial accumulations of oil and gas. Furthermore, the idea of incomplete hydrogenation or incomplete cracking of proto products into asphalt and the complete hydrogenation or complete cracking of the asphalt into oil and gas under natural conditions at depths at which oil and gas are presumed to have been formed seems untenable.

As regards the statement that asphalts and similar substances are intermediate stages between proto products and oil, the relation of many asphalt seepages to the outcrop of oil sands is strongly opposed to this view.

The assumption that fats and waxes are not important sources of oil and gas in nature for the reason that they do not yield proto products upon coalification does not appear to be a logical conclusion in view of the fact that coalification of the type described has not been demonstrated to be an important phenomenon in nature.

F. M. Van Tuyl
Ben H. Parker

Colorado School of Mines
Golden, Colorado
October 1, 1934

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 11 (NOVEMBER, 1934), PP 1549-1551

REVIEWS AND NEW PUBLICATIONS

Geologic Structures. By BAILEY WILLIS and ROBIN WILLIS. 3rd ed., revised. McGraw-Hill, New York (1934). 544 pp., 202 figs. 5.25×7.5 inches. Flexible cover. Price, $4.00.

The third edition of this work, first published in 1923, has been much revised, but the greatest changes seem to be in form and in arrangement, rather than in content. Some important changes have, however, been made which reflect the advances in geologic knowledge and the changing views of the authors. A few of the more important may be noted.

In the second edition (p. 202) it is stated,

> We are thus prohibited from assuming that rocks are materially weakened by heat, except where local conditions may raise the temperature above the normal for any particular depth.

In the present edition (p. 12) it is said,

> Heat weakens the resistance of rocks to pressure, with the result that the extremely strong and rigid outer shell of the earth is underlain by material that is relatively mobile under the action of the tremendous forces that raise mountain chains.

In the present edition, electrical forces have been added to those (gravity, heat energy, and molecular attraction) previously mentioned as agencies of deformation, but its effect is not clearly demonstrated.

Important changes have been made in the chapter on Mechanical Principles (Chapter II). The definitions have been completely rewritten, several terms omitted, and some new ones added, but these still leave much to be desired. For example (p. 21):

> *Strain* is the change of shape or volume produced in a body by stress.
> Distortion is a strain consisting of a change in shape.

It is doubtful whether these will be acceptable to most geologists and they are considerably at variance with the usual definitions.

The relationship between folding and convergence is discussed briefly (pp. 68–69) and their importance in petroleum geology pointed out. A much fuller treatment appears to be justified, and the use of isopach maps in determining age of folding could well be introduced. Examples such as maps showing thickness of Mississippian, and Siluro-Devonian, in the north Mid-Continent fields, would be helpful.

A sharp distinction is made between folds and flexures, the former being defined as "a bend due primarily to horizontal stress transmitted by the strata themselves" and the latter as one "due primarily to vertical movements."

The discussion of fault troughs or grabens (pp. 162–74) has been considerably shortened, which seems unfortunate in view of the growing interest in this type of structure.

The chapter on Analysis of Faulting has been completely rewritten, and thrust faulting treated in greater detail. Strut thrusts are recognized and the statement made that this

is the commonest type of low angle fault, that a large percentage of high angle thrusts belong to this class, and that the basal shear plane, though probably present under every folded or faulted belt, is exposed only in the rarest cases.

This chapter is one of the best in the book.

The chapters on Field Methods, Graphic Methods, and Practical Problems have been much improved by rearrangement and by addition of new material. But since the book is of pocket size and evidently intended as a text and handbook, the space devoted to well logs and columnar sections appears totally inadequate, and quite out of keeping with the excellence of the chapters on Physiographic Expression of Structure (Chap. XII) and on Field Methods (Chap. XIII).

The final chapter has been much condensed from the last five in the previous edition, a section on isostasy is added, and recent developments in gravity measurements are discussed.

On the whole the changes made have served to improve the book and add considerably to its usefulness, and the authors clearly have attempted to correct the errors of the previous editions. In this they have largely succeeded.

J. V. Howell

Ponca City, Oklahoma
October 2, 1934

Historical Geology (First Edition, 1934). By Walter August Ver Wiebe. Photo-lithoprint reproduction of author's manuscript. Edwards Bros., Inc., Ann Arbor, Michigan. 162 pp., 206 figs. Price $2.50.

A profusely illustrated text of historical geology which the author has assembled from many sources and from original material. The photo-lithoprint is clear and easily read and the illustrations are excellent.

The arrangement of the text is somewhat different from that generally used. The discussion of the geologic sequence is the reverse of the usual order. It is apparent that the author has proceeded from the better known facts of the Cenozoic era to the lesser known facts and theories of the Archeozoic era. It has been the aim of the author to introduce the subject to the student so that he finds himself on familar and less difficult ground at the beginning of his course of study. The desired result is to give the student a proper perspective and to prevent confusion of ideas.

A large number of illustrations have been used (206 figs.), more than half of which are new and have never before appeared in print. Many instructive block diagrams, paleogeographic maps, and cross sections of various portions of the United States have been reproduced from original drawings. Publications of the United States Geological Survey have also been drawn on freely.

In scope the author has attempted to present complete information on North America in particular, but has also dealt with the historical geology of the world. The world events of geologic history have been tied to contemporary events in North America. In presenting this material the author has reviewed and incorporated in his book the historical events as set forth in recent geological literature. The text can therefore be said to be up to date and the data used well selected.

The practical student of historical geology will be pleased with the manner of presentation of facts of stratigraphy. The introductory chapter in which

the fundamentals of stratigraphy and paleontology are presented is quite comprehensive and non-technical. The distribution of stratigraphic systems has been shown by means of maps showing present thickness of beds of the system. These maps and text are accompanied by tables of stratigraphic names and by columnar sections.

Considerable space has been devoted to the Archeozoic and Proterozoic eras.

Structural history has been thoroughly discussed and profusely illustrated with cross sections. The profuse use of block diagrams and cross sections helps make this text a valuable contribution to geological literature.

While the book has been planned primarily for the student of geology it will also appeal to the layman.

ROY H. HALL

WICHITA, KANSAS
October 8, 1934

RECENT PUBLICATIONS

GENERAL

"A New Multiple Permeability Apparatus," by F. B. Plummer, Sidon Harris, and John Pedigo. *Amer. Inst. Min. Met. Eng. Tech. Pub. 578* (1934), 13 pp., 5 figs.

GERMANY

"Ueberblick über das nordwestdeutsche erdölhöffige Gebiet" (Review of Prospective Petroleum Province of Northwestern Germany), by Wilhelm Georg Simon, *Inter. Zeit. Bohrtech., Erdölberg. und Geol.* (Vienna), Vol. 42, No. 17–18 (September 15, 1934), pp. 111–17; 10 figs.

TEXAS

"Permian Stratigraphy of Trans-Pecos Texas," by Philip B. King. *Bull. Geol. Soc. America*, Vol. 45 (August 31, 1934), pp. 697–798, Pls. 103–07; 13 figs.

UGANDA

"Petroleum Extravasations in Lake Albert," by E. J. Wayland. *Uganda Protectorate Geol. Survey Dept. Ann. Rept. and Bull. for the Year Ended 31st December, 1933* (Entebbe, 1934), Pt. II (Bull. 1), p. 80.

WEST INDIES

"Rapport sur les résultats d'une mission pour la recherche du pétrole à la Guadeloupe, Juillet–Octobre, 1933" (Report on Results of an Expedition in Search of Petroleum on Guadeloupe, July–October, 1933), by Louis Barrabé. *Annales de l'Office Nat. des Combustibles Liquides* (Paris), No. 4 (July–August, 1934), pp. 625–61; 3 figs., 1 pl., 2 maps.

WYOMING

"Wind River Basin," by C. Max Bauer. *Bull. Geol. Soc. America*, Vol. 45 (August 31, 1934), pp. 665–96, Pls. 94–102; 2 figs.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 11 (NOVEMBER, 1934), PP. 1552-1553

THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to J. P. D. Hull, business manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

FOR ACTIVE MEMBERSHIP

Willard Francis Bailey, Midland, Tex.
E. B. Branson, Henry A. Ley, Alan Bruyere

George M. Hall, Knoxville, Tenn.
Hugh D. Miser, Arthur A. Baker, John B. Reeside, Jr.

Frank Stephen Parker, Los Angeles, Calif.
Roy G. Mead, Parker D. Trask, Silas L. Gillan

Harrison Wilson Straley, III, Princeton, W.Va.
M. King Hubbert, D. Jerome Fisher, Carey Croneis

John Walter Wyckoff, Mount Pleasant, Mich.
George W. Pirtle, Virgil R. D. Kirkham, W. A. Thomas

FOR ASSOCIATE MEMBERSHIP

Harry Draper Easton, Jr., Houston, Tex.
F. Julius Fohs, Burr McWhirt, James H. Gardner

Clinton Engstrand, Bartlesville, Okla.
R. J. Riggs, A. F. Morris, Homer H. Charles

Sylvain Joseph Ghislain Pirson, Tulsa, Okla.
C. A. Heiland, J. Harlan Johnson, F. M. Van Tuyl

Raymond Clayton Powless, Tulsa, Okla.
J. K. Murphy, E. O. Markham, G. C. Siverson

James Weldon Thomas, Dallas, Tex.
Eugene McDermott, Roland F. Beers, J. C. Karcher

FOR TRANSFER TO ACTIVE MEMBERSHIP

Charles Morrison Ross, Tulsa, Okla.
B. B. Weatherby, O. C. Lester, Jr., Jess Vernon

Arthur Karl Wilhelm, Ellsworth, Kan.
J. M. Nisbet, A. F. Morris, Frank T. Clark

CORRECTION

CARL B. RICHARDSON, 204 Nixon Bldg., Corpus Christi, Tex.,
listed in the Supplementary Membership List, p. 1219 of the September *Bulletin*, is a full member, not an associate as there erroneously indicated.

ASSOCIATION COMMITTEES

EXECUTIVE COMMITTEE

William B. Heroy, *chairman*, New York, N. Y.
M. G. Cheney, *secretary*, Coleman, Texas
Frank R. Clark, Tulsa, Oklahoma
Edwin B. Hopkins, Dallas, Texas
L. C. Snider, New York, N. Y.

GENERAL BUSINESS COMMITTEE

Sam M. Aronson (1936)
Arthur A. Baker (1936
R. A. Birk (1936)
M. G. Cheney (1935)
Frank R. Clark (1935)
H. E. Crum (1935)
E. F. Davis (1936)
Joseph A. Dawson (1935)
C. E. Dobbin (1935)
James Terry Duce (1935)
H. B. Fuqua (1935)
M. W. Grimm (1935)
S. A. Grogan (1935)
William B. Heroy (1936)
Edwin B. Hopkins (1935)
John F. Hosterman (1935)
Edgar Kraus (1935)
Roland W. Laughlin (1935)
O. C. Lester, Jr. (1935)
Theodore A. Link (1935)
R. T. Lyons (1935)
Roy G. Mead (1935)
A. F. Morris (1935)
L. Murray Neumann (1936)
Philip E. Nolan (1935)
Clarence F. Osborne (1935)
Gayle Scott (1935)
A. L. Selig (1935)
L. C. Snider (1935)
J. D. Thompson, Jr. (1936)
Wallace C. Thompson (1935)
J. M. Vetter (1936)
Paul Weaver (1935)
Maynard P. White (1935)
E. A. Wyman (1935)

RESEARCH COMMITTEE

Donald C. Barton (1936), *chairman*, Humble Oil and Refining Company, Houston, Texas
A. I. Levorsen (1935), *vice-chairman*, Tide Water Oil Company, Houston, Texas

C. E. Dobbin (1935)
Alex W. McCoy (1935)
C. V. Millikan (1935)
L. C. Snider (1935)
L. C. Uren (1935)
Harold W. Hoots (1936)
R. S. Knappen (1936)
W. C. Spooner (1936)
Parker D. Trask (1936)
M. G. Cheney (1937)
Robert H. Dott (1937)
K. C. Heald (1937)
F. H. Lahee (1937)
H. A. Ley (1937)
R. C. Moore (1937)
F. B. Plummer (1937)

REPRESENTATIVE ON DIVISION OF GEOLOGY AND GEOGRAPHY NATIONAL RESEARCH COUNCIL

R. S. Knappen (1937)

GEOLOGIC NAMES AND CORRELATIONS COMMITTEE

Ira H. Cram, *chairman*, Pure Oil Company, Tulsa, Oklahoma

John G. Bartram
M. G. Cheney
Alexander Deussen
B. F. Hake
G. D. Hanna
M. C. Israelsky
A. I. Levorsen
C. L. Moody
R. C. Moore
Ed. W. Owen
J. R. Reeves
W. A. Thomas

TRUSTEES OF REVOLVING PUBLICATION FUND

Frank R. Clark (1935)
Charles H. Row (1936)
Ralph D. Reed (1937)

TRUSTEES OF RESEARCH FUND

Alex W. McCoy (1935)
Robert H. Dott (1936)

FINANCE COMMITTEE

W. E. Wrather (1935)
Joseph E. Pogue (1936)
E. DeGolyer (1937)

COMMITTEE ON APPLICATIONS OF GEOLOGY

F. H. Lahee, *chairman*, Box 2880, Dallas, Texas

William H. Atkinson
Arthur E. Brainerd
H. A. Buehler
Hal P. Bybee
Frank R. Clark
Herschel H. Cooper
Carey Croneis
H. B. Hill
Earl P. Hindes
Marvin Lee
S. E. Slipper
E. K. Soper
J. M. Vetter

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 11 (NOVEMBER, 1934), P. 1554

Memorial

THOMAS KENNERLY HARNSBERGER

Thomas Kennerly Harnsberger died in Highland Park, Illinois, on September 27, 1934. His death was the result of ill health which had forced him to retire from active work in 1931. He is survived by his widow, parents, and two sisters.

Although he maintained a home in Tulsa, Oklahoma, much of his time during his last few years of life was spent in Arizona and Illinois in order to obtain the most desirable seasonal climate.

T. K. Harnsberger was born in Elkton, Virginia, on April 26, 1889. He prepared himself for the University of Virginia at Fishburn Military School at Waynesboro, Virginia, and at the Harrisonburg High School at Harrisonburg, Virginia. His Bachelor's and Master's degrees were obtained from the University of Virginia, where he completed his training in 1912. Post-graduate work was taken at George Washington University. He majored in geology and analytical chemistry, with graduate work in geology. His professors state that he was a very capable student, especially in mathematics, wherein he distinguished himself. While at the University of Virginia, he was elected to Phi Beta Kappa and received other scholastic honors.

Following his university training, he accepted a position with the Virginia Geological Survey. His assignment was the investigation of coal deposits in southwestern Virginia. Later he represented both the United States Geological Survey and the Virginia Survey and completed the bulletin on the coal deposits of Taswell County, Virginia.

In July, 1917, he joined the geological staff of Roxana Petroleum Corporation (Shell) and was assigned to work in the Rocky Mountain region, where he remained until December, 1920, when he went to South America with the Asiatic Petroleum Company (Shell). Returning from his foreign assignment in 1922, he was made chief geologist of the Wolverine Petroleum Corporation at Tulsa, Oklahoma. Later he was made division geologist in charge of the land and geological departments for Shell in the Mid-Continent area. He retained this position until forced to resign in 1931 on account of ill health.

Tom, or T. K. as he was affectionately known by his many friends, was one of few words, but whenever called upon, he was found to hold opinions that were sound and well expressed. His consideration for those working under his supervision was reason for their great admiration of him. His multitude of friends mourn his passing and the world has lost a most lovable character. While Tom has already proved that he was among the few to approach the top of their profession, further achievements were expected and his death was very untimely.

ROSCOE E. SHUTT

TULSA, OKLAHOMA
October, 17, 1934

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 11 (NOVEMBER, 1934), PP. 1555-1558

AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

JOHN F. HOSTERMAN, geologist for the Amerada Petroleum Corporation, has been moved from San Angelo to Fort Worth, Texas, to assist A. R. DENISON, district geologist, with headquarters at Fort Worth.

V. C. ILLING, professor in the Royal School of Mines, South Kensington, London, addressed the Fort Worth Geological Society, Fort Worth, Texas, September 26. Professor Illing, as consultant for the Pearson interests (Amerada and Rycade), has been spending a few months in the oil fields of the United States.

W. D. ANDERSON, geologist with the Amerada Petroleum Corporation at San Antonio, has been transferred to the company offices which were recently moved from San Angelo to Midland, Texas. J. R. DAY and S. R. SELF were transferred from San Angelo to Midland. JOHN M. HILLS has been employed on the geological staff at the new Midland offices.

J. P. THOMPSON, formerly Amerada assistant geologist at Tyler, is now district geologist at San Antonio, Texas.

FRANK C. GREENE has been stationed temporarily at Kansas City, Missouri, for the Missouri Geological Survey and Water Resources.

WILLARD J. CLASSEN, for the past ten years in the employ of the Associated Oil Company, has opened offices in Suite 1091–1093 Mills Building, San Francisco, as a consulting geologist and petroleum engineer. Associated with him is L. R. MORETTI, consulting mining engineer.

M. A. HARRELL, of the United States Geological Survey, has recently prepared a report on "Ground Water Resources of the Ohio River Basin," as special regional water consultant, for the National Resources Board.

JOHN FITTS, geologist of Ada, Oklahoma, presented a paper, "Correlations and Mountain Making Movements in the Ouachitas," before the Tulsa Geological Society, Monday evening, October 1.

MONROE G. CHENEY, Coleman, Texas, secretary-treasurer of the A. A. P. G., presented his papers entitled, "The Concho Arch" and "Geological Factors Affecting Well Spacing," before the Fort Worth Geological Society, October 9, in the geology laboratory, Texas Christian University.

WALLACE LEE addressed the North Texas Geological Society on different phases of the work he has been supervising for the past six months in Young, Stephens, and Throckmorton, Texas, for the United States Geological Survey.

At the regular monthly meeting of the San Antonio Geological Society, October 1, J. E. PEARCE, head of the department of anthropology, University of Texas, gave an illustrated lecture, "Tales That Dead Men Tell."

J. B. SOUTHER has changed his address from Laredo, Texas, to 1131 South Tenth Street, Lincoln, Nebraska.

ROBERT BROWN, formerly of 2107 Blodgett Street, Houston, Texas, may now be addressed at 201 West Midland, Shawnee, Oklahoma.

ALDEN S. DONNELLY, of the Honolulu Oil Corporation, Midland, Texas, has been elected president of the Midland Geological Society. FRED WILCOX, of the Magnolia Petroleum Company, is newly named vice-president, and FRED S. WRIGHT, of The California Company, is secretary-treasurer.

CHARLES A. STEWART, geologist, in charge of the San Antonio office of the United Production Corporation, has been transferred to Beeville, Texas. The San Antonio office has been closed.

HOWARD E. NESSLY, consulting geologist, is located at 415 Milam Building, San Antonio, Texas.

FRANK REEVES, formerly of the United States Geological Survey, L. G. PUTNAM, formerly with the Western Gulf Oil Company, and WILLARD A. FINDLAY, formerly with the Superior Oil Company, are in Australia with D. DALE CONDIT, of California, working for Oil Search Limited of Sydney. Condit reports that this company is successfully applying geology to exploratory work in the Roma district of Queensland, where a structure, mapped nearly a year ago by FRANK A. MOSS, has been drilled and the result seems to be a commercial gas well, the preliminary tests indicating "wet" gas with a volume close to 500,000 cubic feet per day.

CHARLES N. GOULD is director of the Materials Survey of the Federal Emergency Relief Administration in Oklahoma. Approximately twenty people are working in Oklahoma City. The Tulsa office, in charge of E. G. WOODRUFF, employs several people

GRANT W. SPANGLER is working for the Stanolind Oil and Gas Company at Tulsa.

R. R. PATTON is with the Standard Oil Company in Venezuela.

C. SCHLUMBERGER is president, M. SCHLUMBERGER is vice-president, and E. G. LEONARDON is vice-president and treasurer of the new organized Schlumberger Well Surveying Corporation (formerly Schlumberger Electrical Prospecting in Texas, and Schlumberger Electrical Coring in California), located in the Experson Building, Houston, Texas.

ALEX M. ALEXANDER, formerly with the Empire Oil and Refining Company, was killed in an explosion in a chemical laboratory in New York on September 10, 1934.

The Houston Geological Society in annual meeting, October 11, elected the following officers for the ensuing year: president, W. F. BOWMAN, Tide Water Oil Company; vice-president, JOHN C. MILLER, The Texas Company; and secretary-treasurer, PHIL F. MARTYN, The Houston Oil Company of Texas.

ROBERT E. KING has changed his address from 2424 Fredericksburg Road, San Antonio, Texas, to care of C. y S. Aristizabal, Puerto Berrio, Colombia.

J. M. ARMSTRONG, geologist, Sinclair Oil and Gas Company, Fort Worth, Texas, has moved his headquarters to Midland, Texas.

The Dallas Petroleum Geologists held their annual election of officers on October 15 and the followering were elected: chairman, L. J. PEPPERBERG, First National Bank Building; vice-chairman, H. J. HAWLEY, The California Company; and secretary-treasurer, CHARLES B. CARPENTER, United States Bureau of Mines.

T. S. LOVERING has changed his address from the United States Geological Survey, Golden, Colorado, to Department of Geology, University of Michigan, Ann Arbor.

LOWELL K. MOWER, formerly of Wassenaar, Holland, may now be addressed in care of U. B. O. T., 15 Abercromby Street, Port of Spain, Trinidad, B. W. I.

At a meeting of the Midland Geological Society, September 21, the following officers were elected: president, ALDEN S. DONNELLY, Honolulu Oil Company; vice-president, FRED H. WILCOX, Magnolia Petroleum Company; and secretary-treasurer, FRED S. WRIGHT, The California Company.

ERNEST S. PRATT, district geologist in Kansas for the Shell Petroleum Corporation for several years, has resigned to engage in independent work in Wichita, Kansas.

L. MURRAY NEUMANN, who has been with The Carter Oil Company, Tulsa, Oklahoma, for 19 years and who has been chief geologist of that company for more than 16 years, was recently appointed consulting geologist for The Carter Company. This change will give him an opportunity to devote more time to the broader geological problems.

The annual meeting of the Geological Society of America will be held in the Chester Dewey Building, River Campus, University of Rochester, at Rochester, New York, December 27, 28, and 29.

JOHN Y. SNYDER, Shreveport, Louisiana, a past-president of the Association, was elected to honorary membership in Sigma Xi when the chapter of that society was established recently at Tulane University, New Orelans, Louisiana. Election was by virtue of notable contributions in the science of geology, although Mr. Snyder's degree, in 1897, was B.E. in architectural engineering.

After a lapse of a quarter of a century, since the GILBERT D. HARRIS Survey (1898–1909), Louisiana now has a State Survey. The Legislature of 1934 passed a measure creating a Geological Survey of Louisiana as a Division of the Department of Conservation and directed the Commissioner of Conservation to appoint a State geologist. To further the program of this survey, Commissioner of Conservation ROBERT S. MAESTRI and Director HENRY V. HOWE of the School of Geology of Louisiana State University, on September 26, 1934, entered into an agreement whereby the research program of this survey would be conducted by the School of Geology in coöperation with the Department of Conservation. The commission has appointed CYRIL K. MORESI, formerly geologist of the Conservation Department's Bureau of Scientific Research and Statistics, to the position of State geologist, and

JAMES H. MCGUIRT has been appointed assistant. The State geologist's office is in the Department of Conservation at New Orleans. The assistant's headquarters will be in the School of Geology of the Louisiana State University at Baton Rouge.

The American Association of Petroleum Geologists will hold its 20th annual meeting at Wichita, Kansas, March 21, 22, and 23, 1935. E. C. MONCRIEF, Derby Oil Company, Wichita, is chairman of the local arrangements committee.

STEPHEN H. ROOK is engaged in micropaleontological work for the United Gas System at Houston, Texas.

HARLEY S. GIBBS has his office as a consulting geologist at 416 Zara Street, Pittsburgh, Pennsylvania.

THOMAS L. KESLER, Box 86, Salisbury, North Carolina, has completed a season of temporary work as junior geologist with the United States Geological Survey.

RICHARD HENRY DANA, formerly with the Wisconsin Geological Survey, is now with the Stanolind Oil and Gas Company at Carlsbad, New Mexico.

The Pacific Section of the Association, at the University Club, Los Angeles, October 19, listened to BEN F. HAKE discuss "Some Phases of the Geology and Oil Prospects of Alberta, Canada."

P. L. KELLER is an independent operator at 244 Natalen Avenue, San Antonio, Texas.

ED. BLOESCH read a paper on "Observations on Oklahoma Gravel Deposits," and O. E. STONER read a discussion of "Surface Structure in Cretaceous in Western Kansas," before the Tulsa Geological Society, October 22, 1934.

The Shawnee Geological Society met, October 22, 1934, and elected the following officers: president, H. H. ARNOLD, JR., The Texas Company; vice-president, H. W. O'KEEFFE, Phillips Petroleum Company; and secretary-treasurer, W. M. GUTHREY, The Texas Company.

At a meeting of the East Texas Geological Society held October 19, in Tyler, Texas, the following new officers were installed: president, F. H. SCHOUTEN, Stanolind Oil and Gas Company; vice-president, WALLACE RALSTON, Sun Oil Company; and secretary-treasurer, JOHN W. CLARK, Magnolia Petroleum Company.